Ion Trap Quantum Information Processing in Innsbruck
Current Status and Future Plans

Rainer Blatt
Institute of Experimental Physics, University of Innsbruck,
Institute of Quantum Optics and Quantum Information,
Austrian Academy of Sciences

- Ca^+ for quantum information processing: qubits
- Ca^+ experiments, techniques and state of art
- CNOT gate operation, error budget
- interfacing quantum information: cavity QED with Ca^+
- segmented ion traps and future work

universität innsbruck

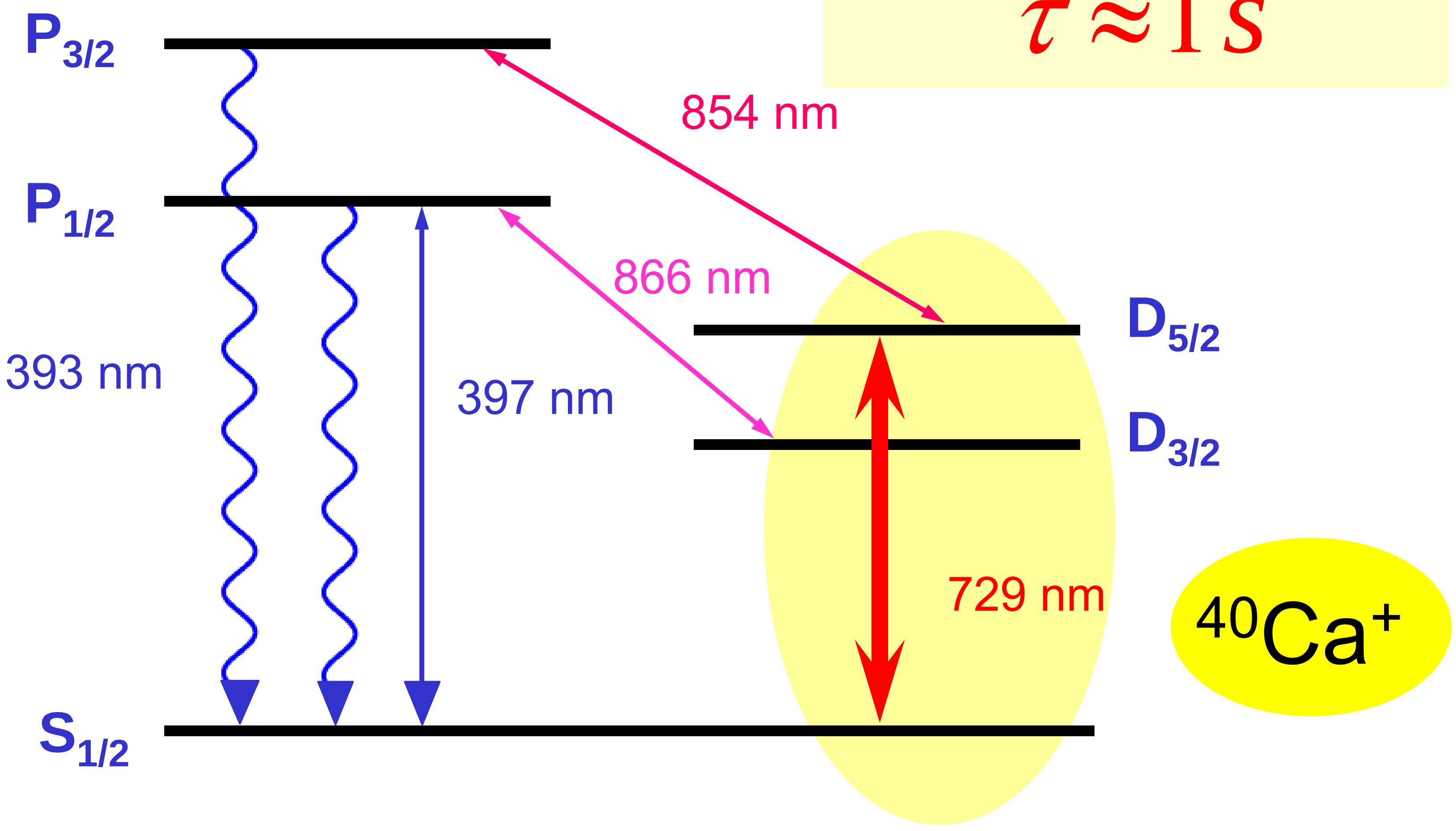
AG Quantenoptik und Spektroskopie

€ FWF SFB QUEST QGATES Industrie Tirol IQI GmbH
FWF bm:bwk
$ ARDA

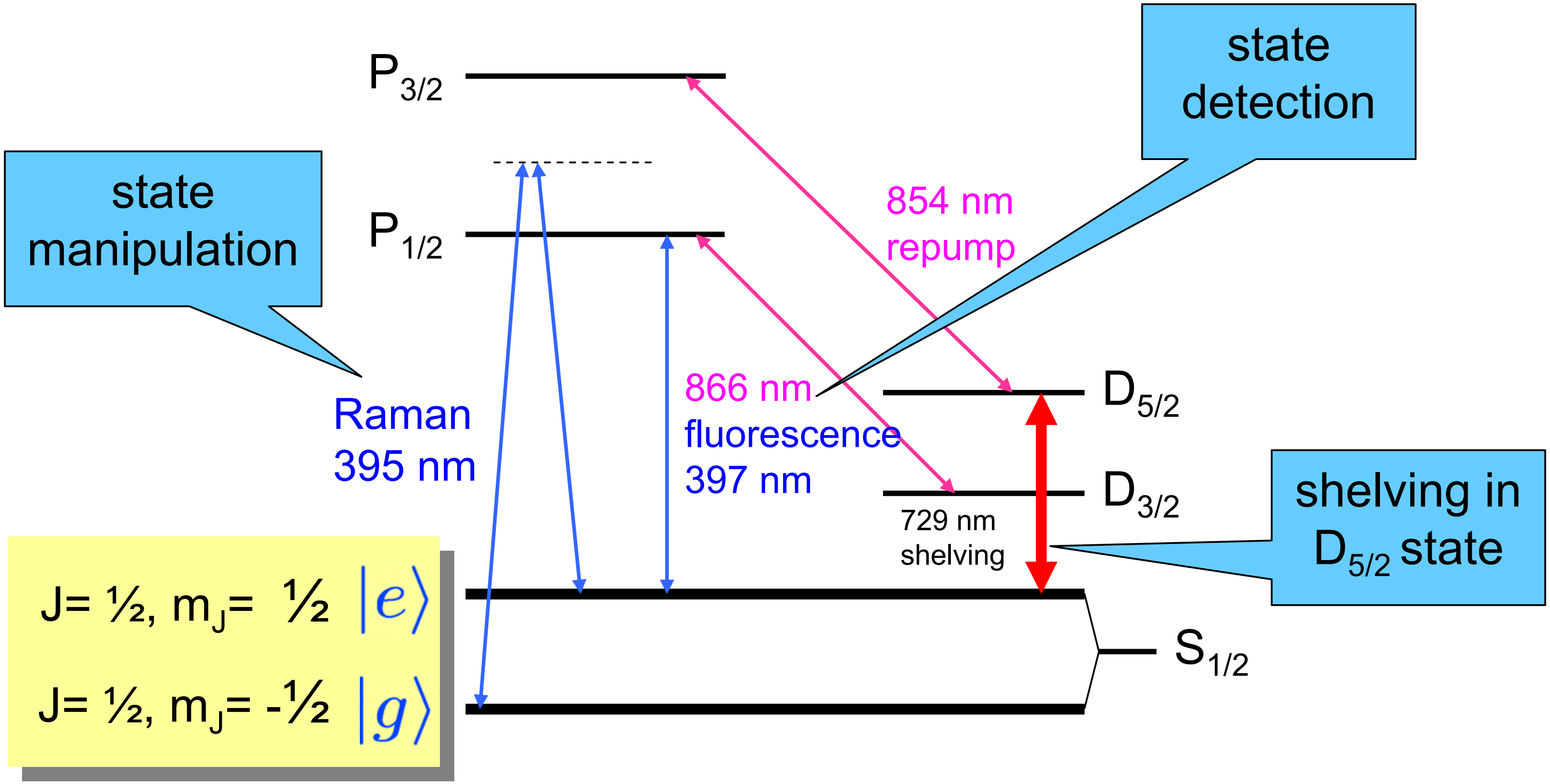
Level scheme of Ca^+

qubit on narrow S - D quadrupole transition

$$\tau \approx 1\,s$$

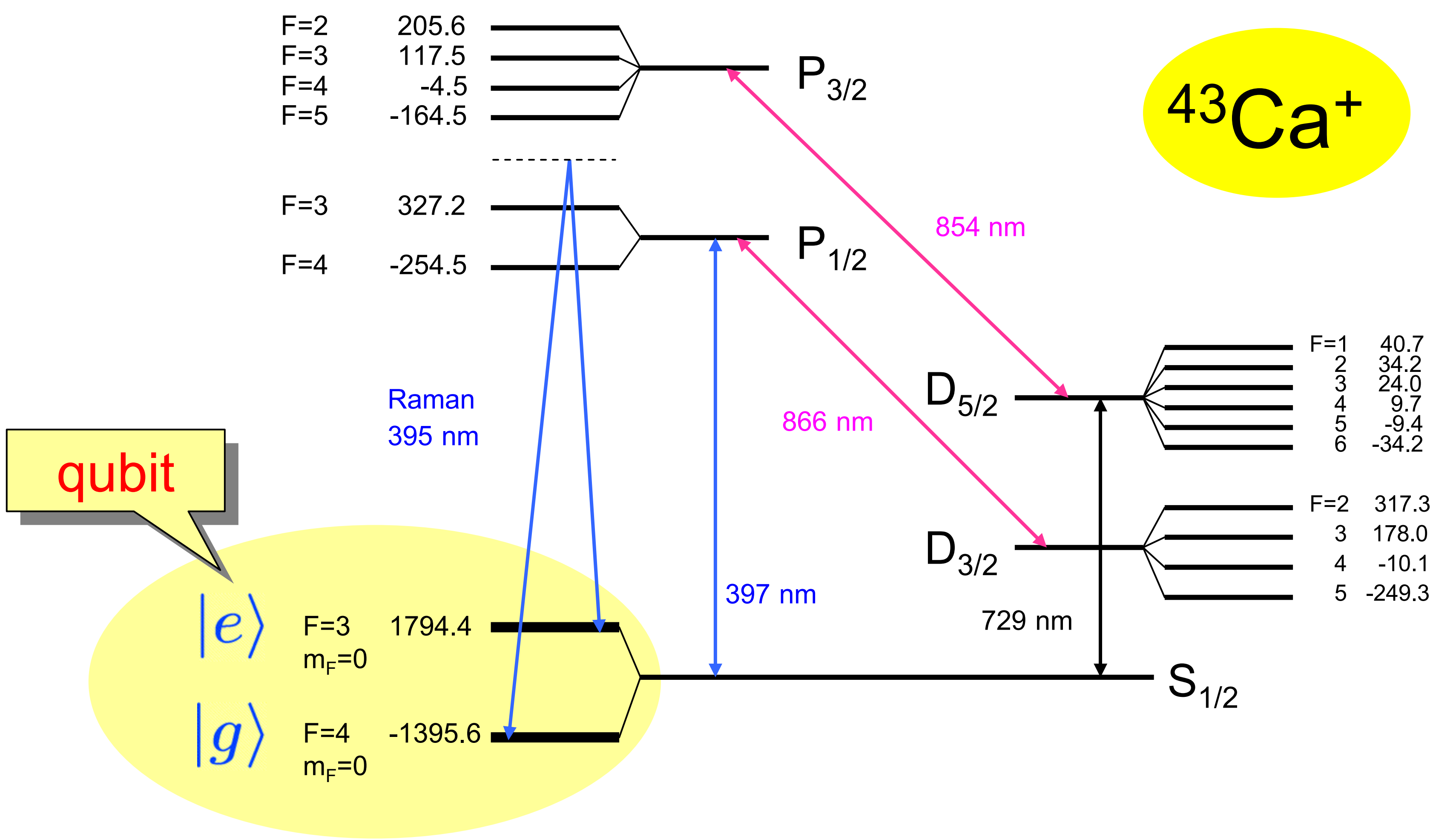


$^{40}Ca^+$: Zeeman substates



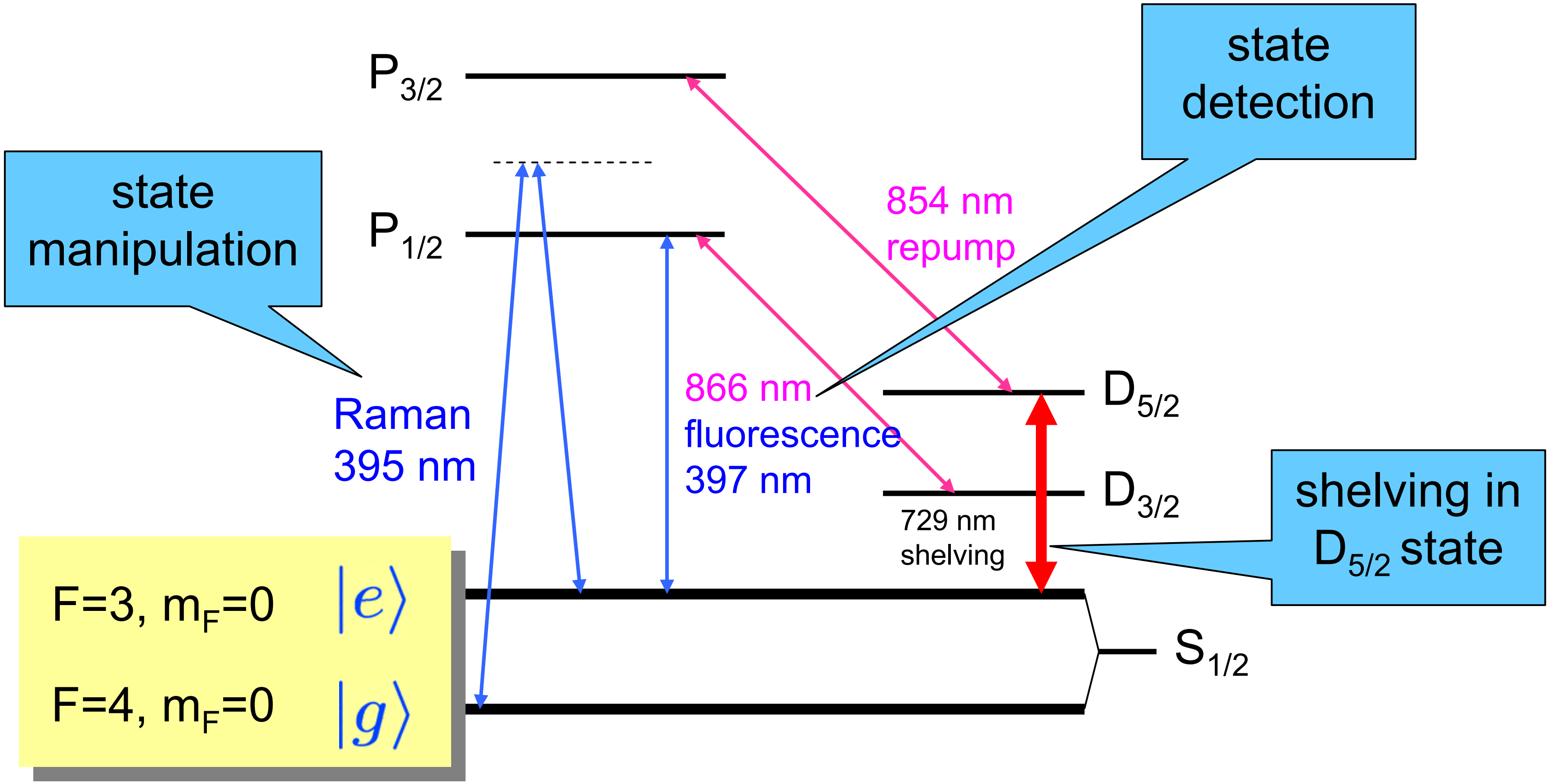
linear Zeeman effect,
requires decoherence free subspace

Level scheme of $^{43}Ca^+$



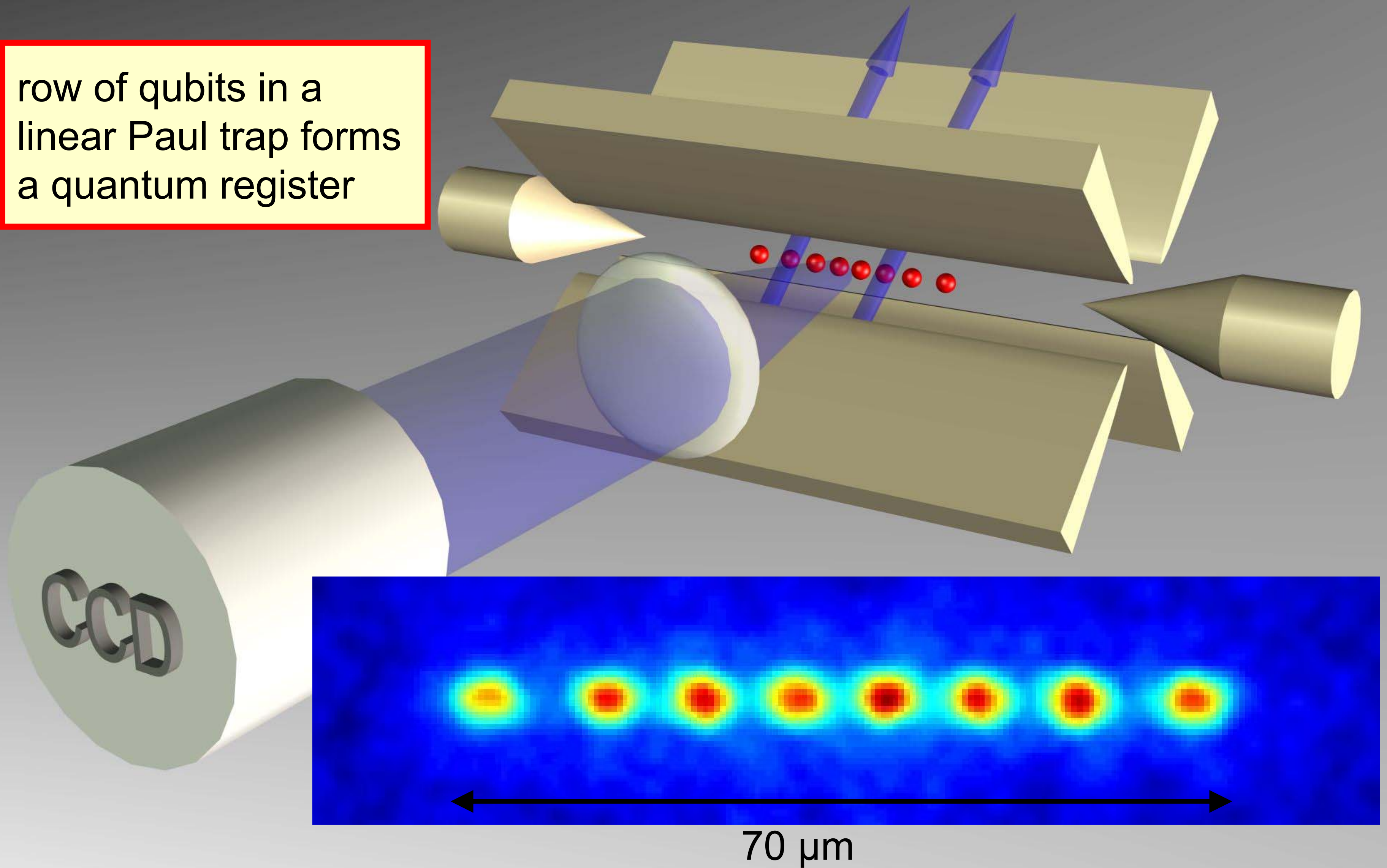
all frequencies in MHz

$^{43}Ca^+$: manipulation and detection

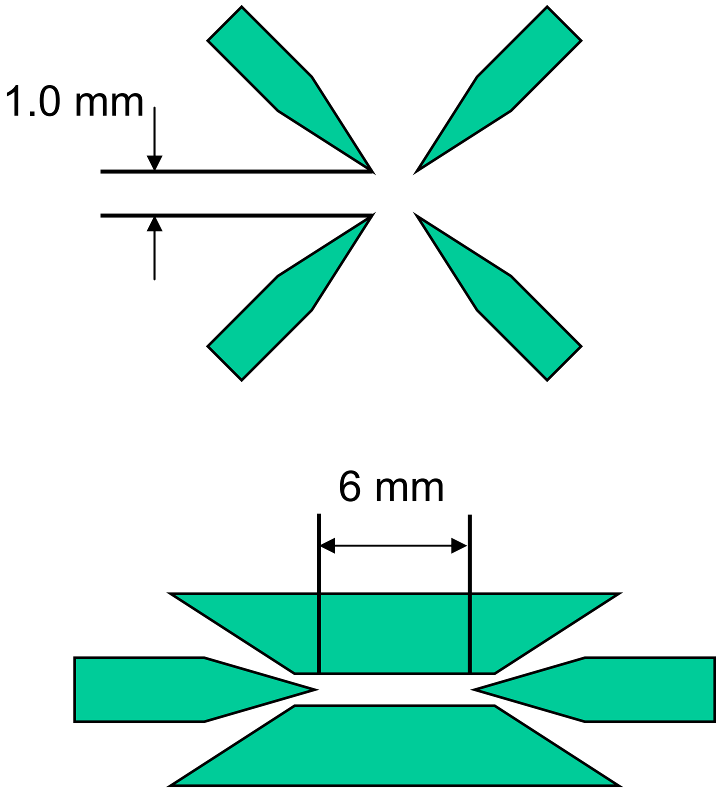


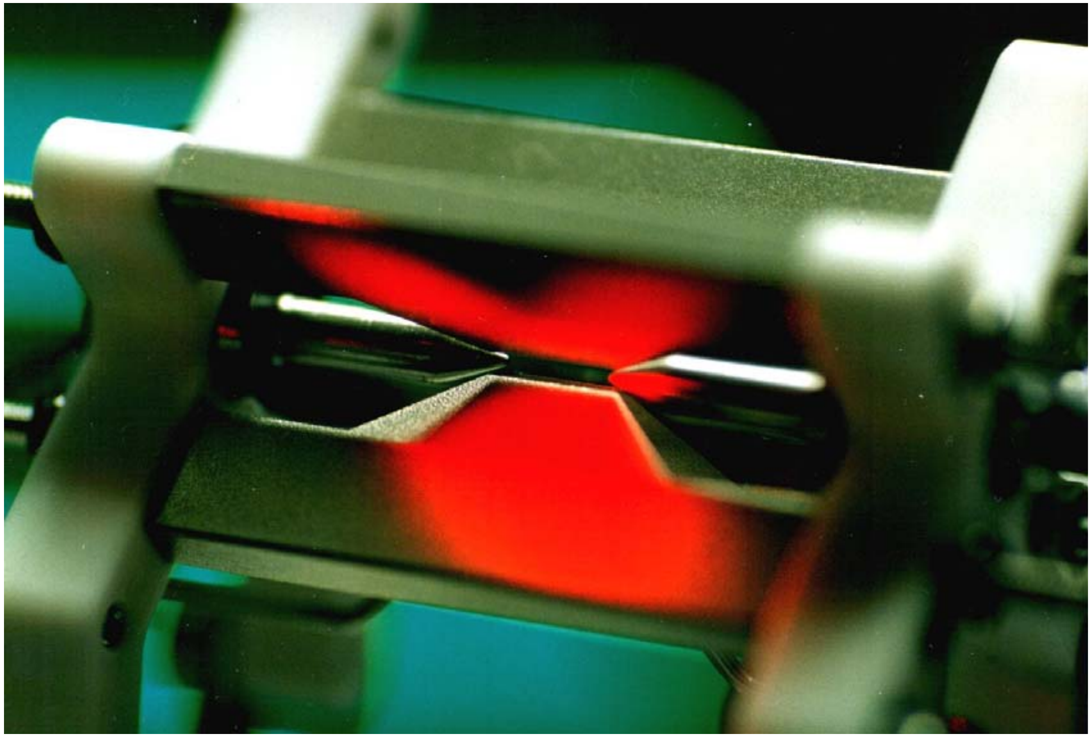
String of $^{40}Ca^{+}$ ions in a linear Paul trap

row of qubits in a linear Paul trap forms a quantum register



Innsbruck linear ion trap (2000)

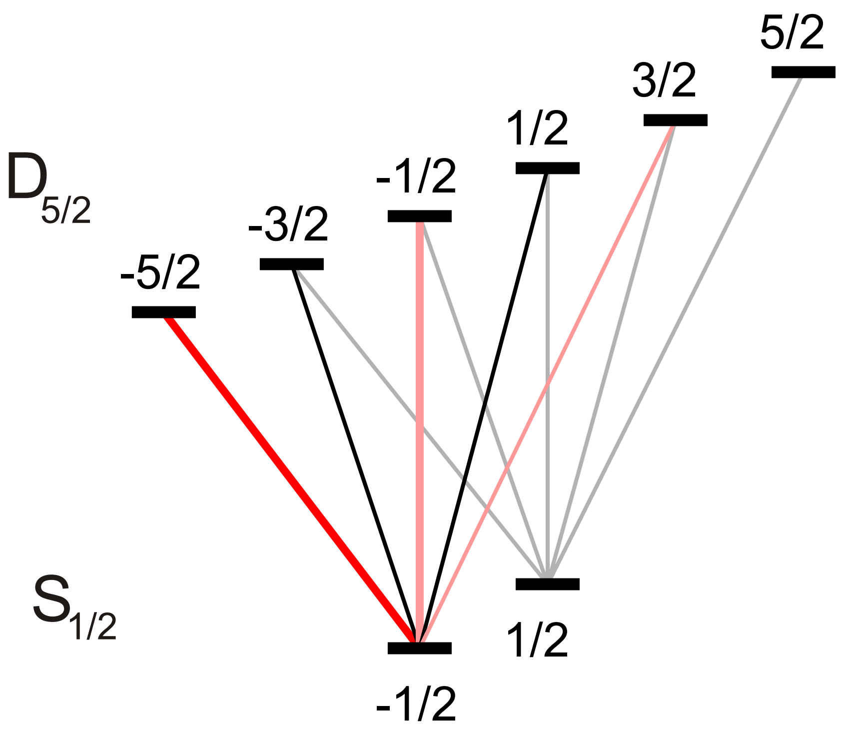




$$\omega_z \approx 0.7 - 2\,\mathrm{MHz} \qquad \omega_{x,y} \approx 1.5 - 4\ \mathrm{MHz}$$

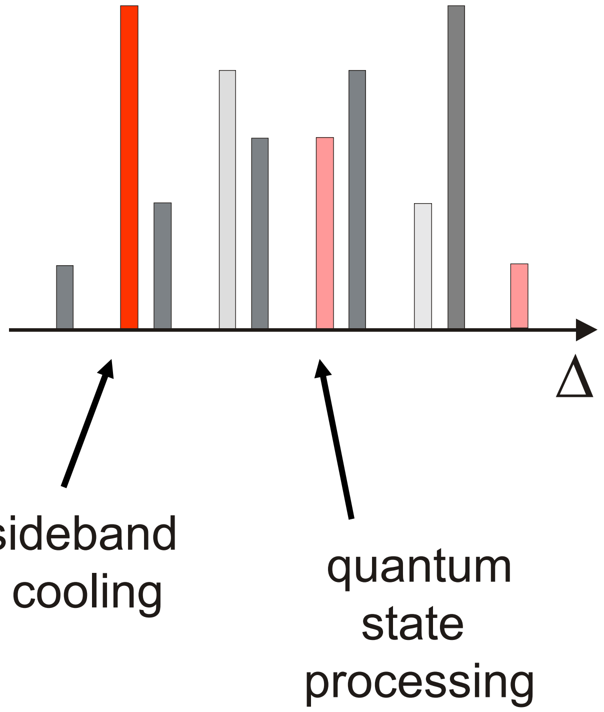
Spectroscopy of the $S_{1/2}$ – $D_{5/2}$ transition

Zeeman structure in non-zero magnetic field:



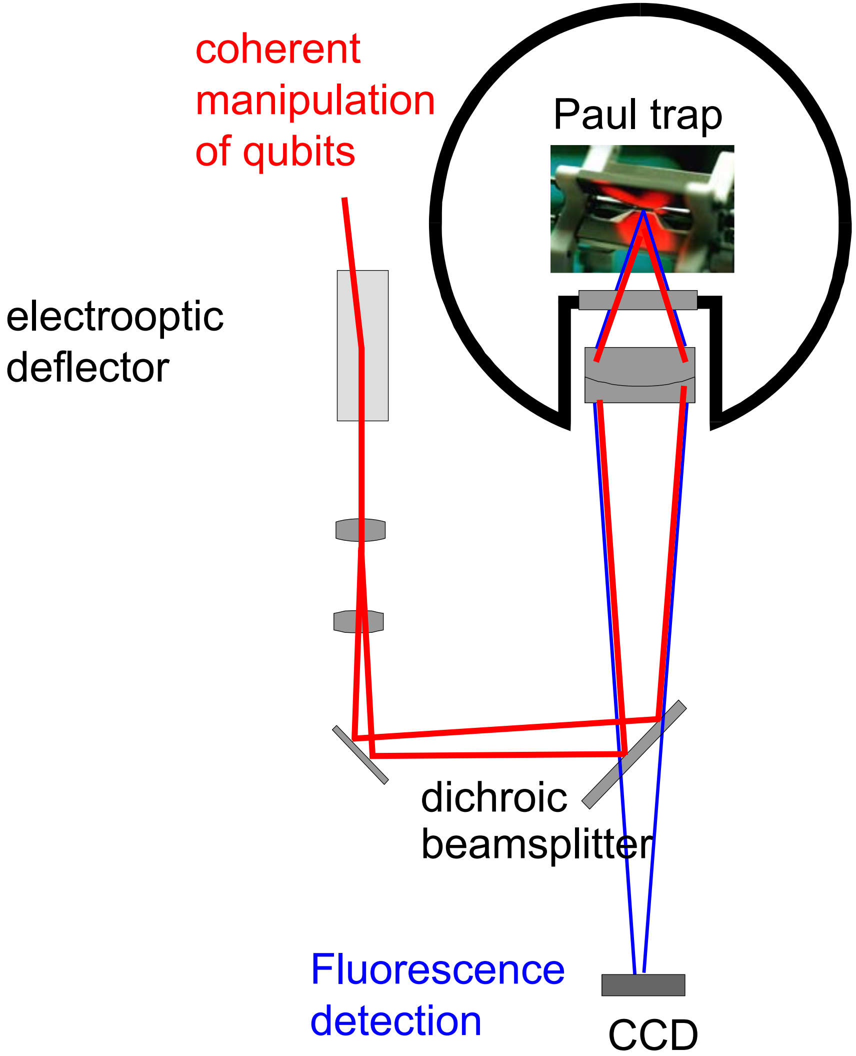
2-level-system:

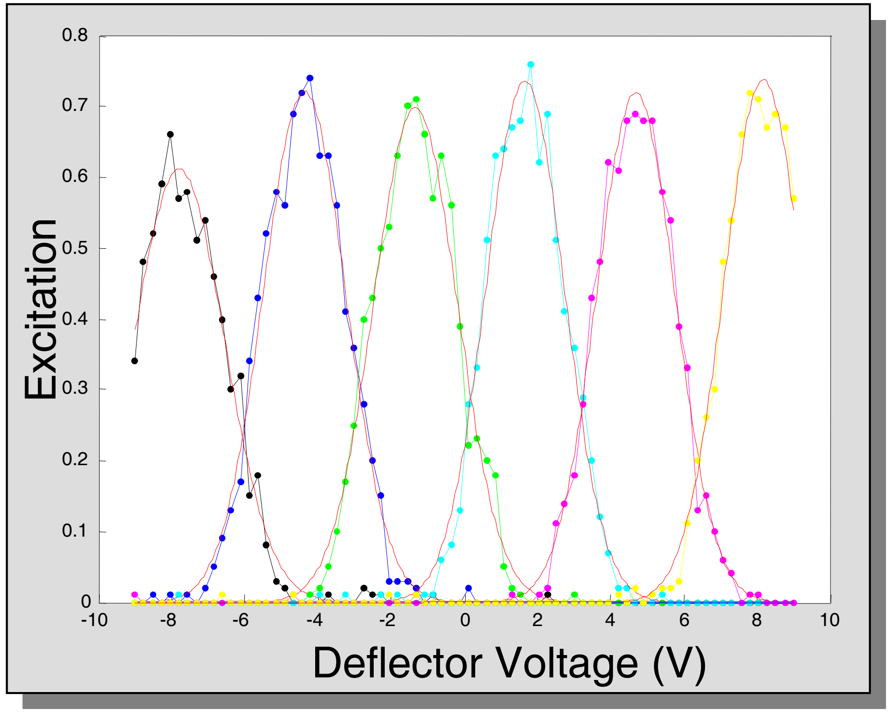
$$-1/2 \longrightarrow -5/2(-1/2)$$



+ vibrational degrees of freedom

Addressing of individual ions

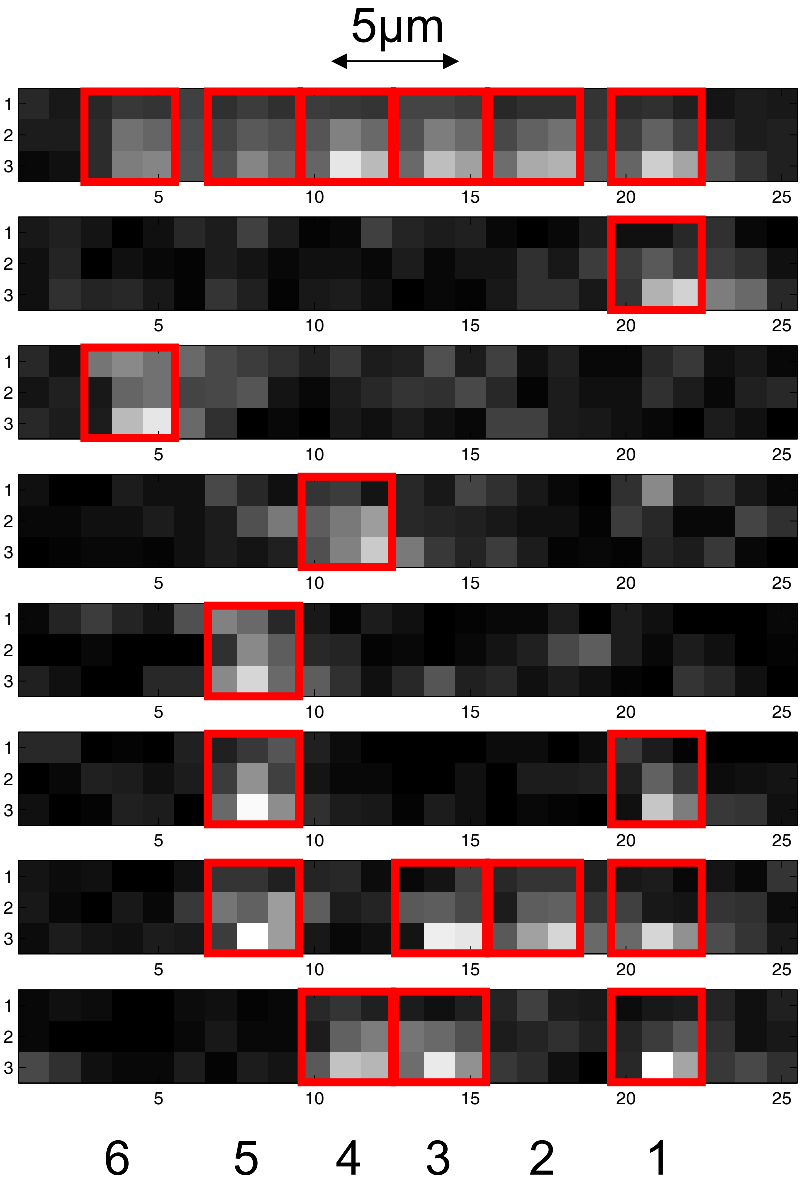




- inter ion distance: ~ 4 µm
- addressing waist: ~ 2.5 µm

< 0.1% intensity on neighbouring ions

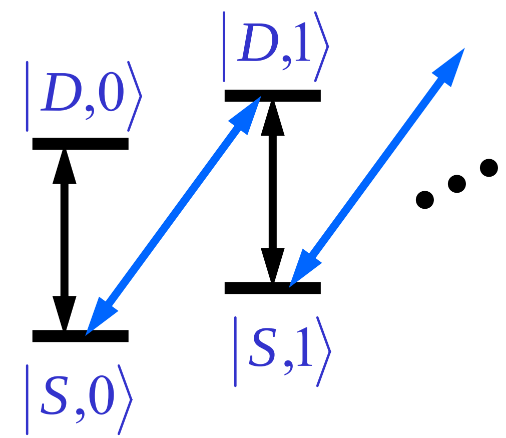
Detection of 6 individual ions



state detection on a CCD camera

all ions in |S>	$\|SSSSSS\rangle$
ion 1 in |S>	$\|DDDDDS\rangle$
ion 6 in |S>	$\|SDDDDD\rangle$
ion 4 in |S>	$\|DDSDDD\rangle$
ion 5 in |S>	$\|DSDDDD\rangle$
ions 1 and 5 in |S>	$\|DSDDDS\rangle$
ions 1,2,3, and 5 in |S>	$\|DSSSSS\rangle$
ions 1,3 and 4 in |S>	$\|DDSSDS\rangle$

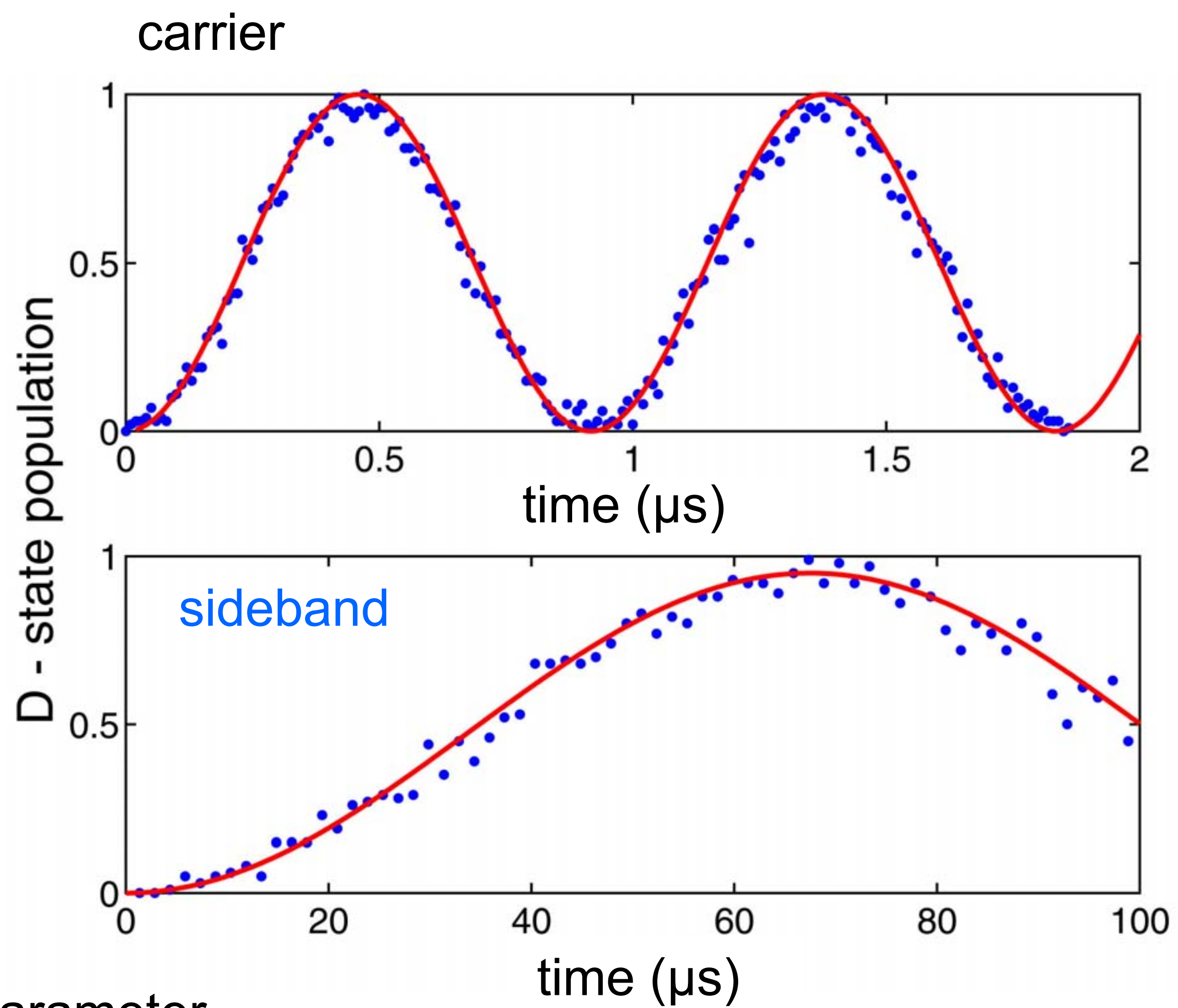
Coherent state manipulation



carrier and sideband
Rabi oscillations
with Rabi frequencies

$$\Omega, \quad \eta\Omega\sqrt{n+1}$$

$\eta = kx_0$ Lamb-Dicke parameter



Ca^+ ion trap quantum information processing

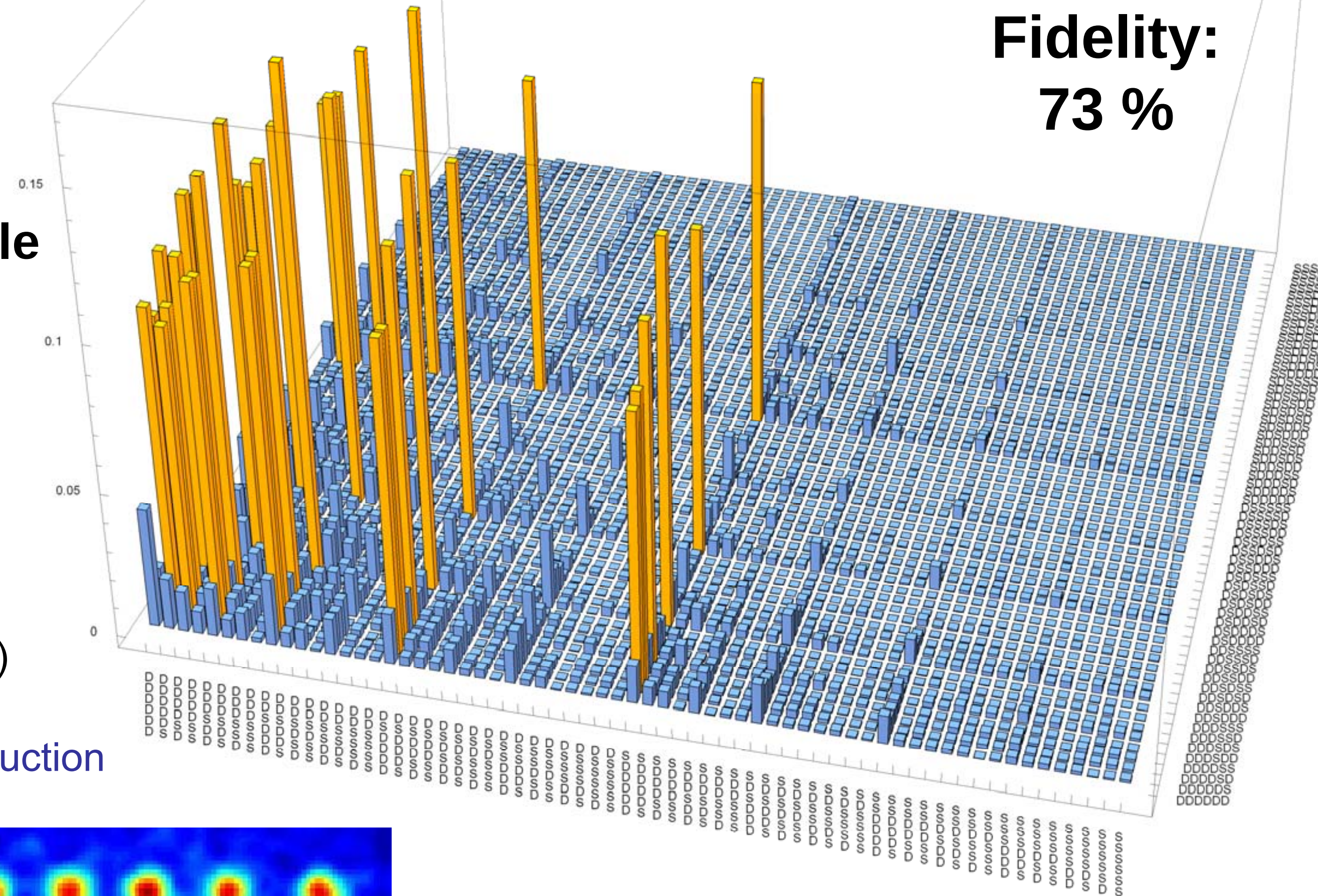
achievements

Deutsch-Jozsa algorithm	Nature 421, 48 (2003)
Cirac-Zoller CNOT gate operation	Nature 422, 408 (2003)
GHZ, W states, conditional operations	Science 304, 1478 (2004)
Teleportation	Nature 429, 734 (2004)
Quantum state tomography	PRL 92, 220402 (2004)
Long-lived entanglement	Appl. Phys. B 81, 151 (2005)
4-8 qubit entanglement	Nature 438, 643 (2005)
Precision spectroscopy with entangled states	to be published
Quantum Process Tomography	to be published

Six-Ion W-state

$$\Psi_6 = \frac{1}{\sqrt{6}}(|DDDDDS\rangle + |DDDDSD\rangle + |DDDSDD\rangle + |DDSDDD\rangle + |DSDDDD\rangle + |SDDDDD\rangle)$$

$$|\rho_{ij}|$$



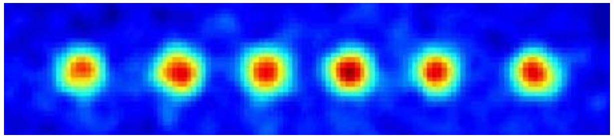
Fidelity: 73 %

Genuine 6-particle entanglement !

- 6-particle entanglement can be distilled from the state (W. Dür)
- Entanglement witness detects 6-particle entanglement (O. Gühne)

- error bars in the reconstruction process ?

22.4.2005

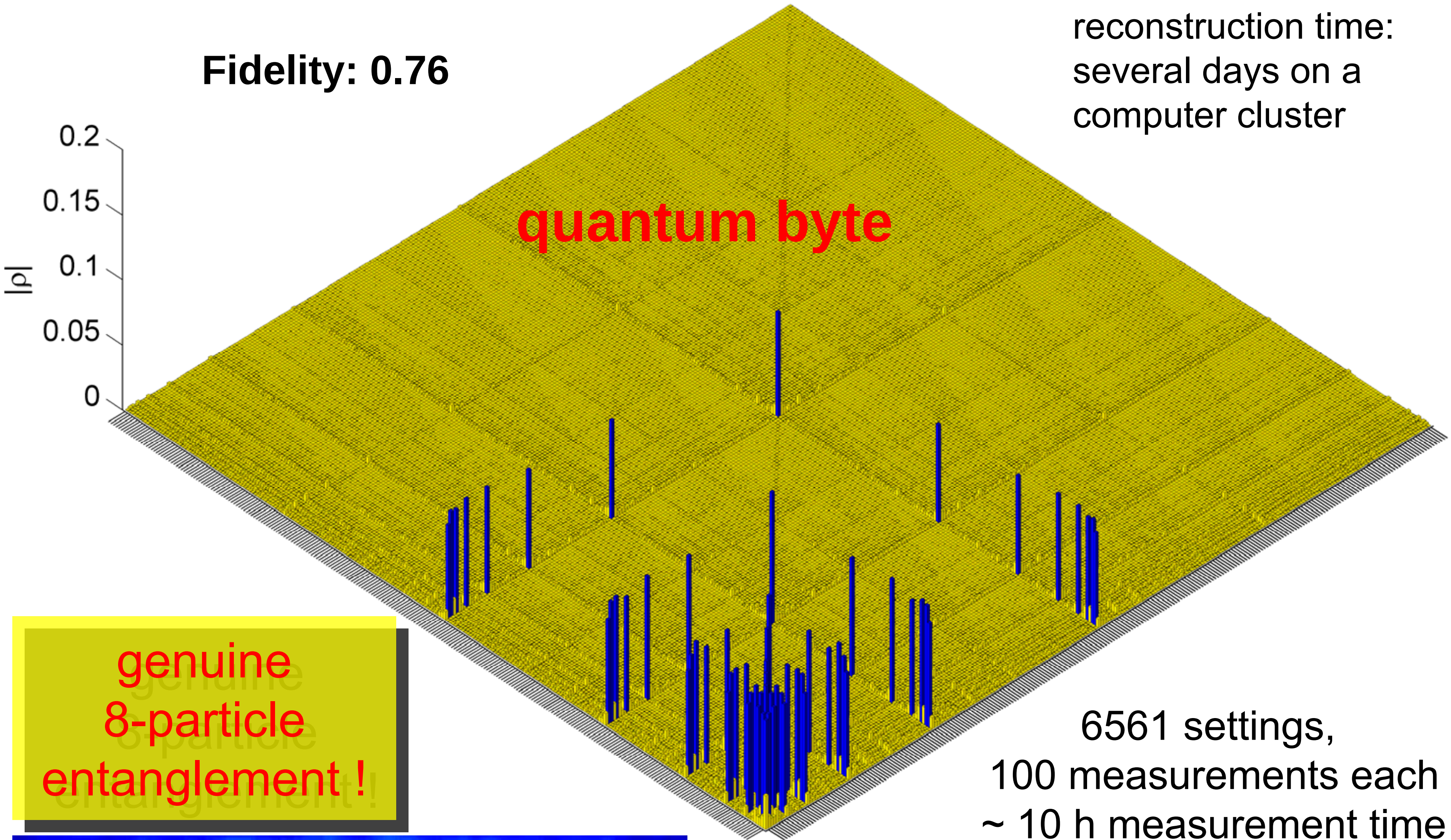


729 settings, measurement time ~ 40 min.

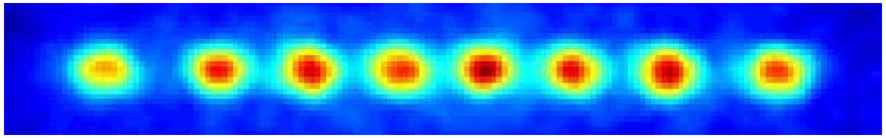
Eight - ion W state

Fidelity: 0.76

reconstruction time:
several days on a
computer cluster



genuine
8-particle
entanglement !



6561 settings,
100 measurements each
~ 10 h measurement time

H. Häffner et al., Nature **438**, 643 (2005)

Future Ca^+ experiments ….

- entanglement swapping
- entanglement purification
- error correction protocols (3, 5, 7 ions)
- logical qubit
- algorithms (Shor, Grover)
- scalability
- the "real" quantum computer …
- …

…
the
generic
list …

BUT everything relies crucially on the availability of a high fidelity two-ion gate operation.

The Cirac-Zoller CNOT gate operation with 2 ions

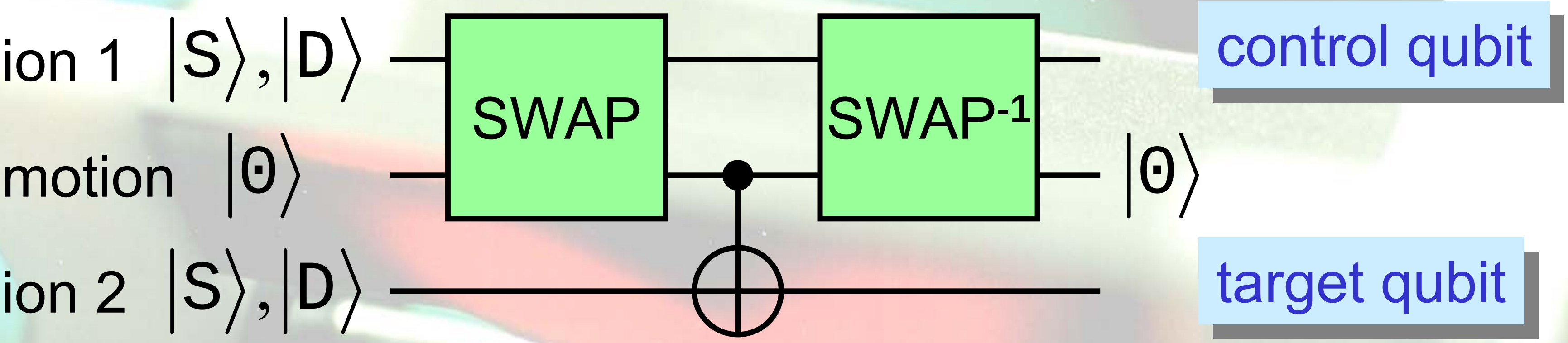
allows the realization of a
universal quantum computer !

$$
\begin{aligned}
|0\rangle|0\rangle &\rightarrow |0\rangle|0\rangle \\
|0\rangle|1\rangle &\rightarrow |0\rangle|1\rangle \\
|1\rangle|0\rangle &\rightarrow |1\rangle|1\rangle \\
|1\rangle|1\rangle &\rightarrow |1\rangle|0\rangle
\end{aligned}
$$

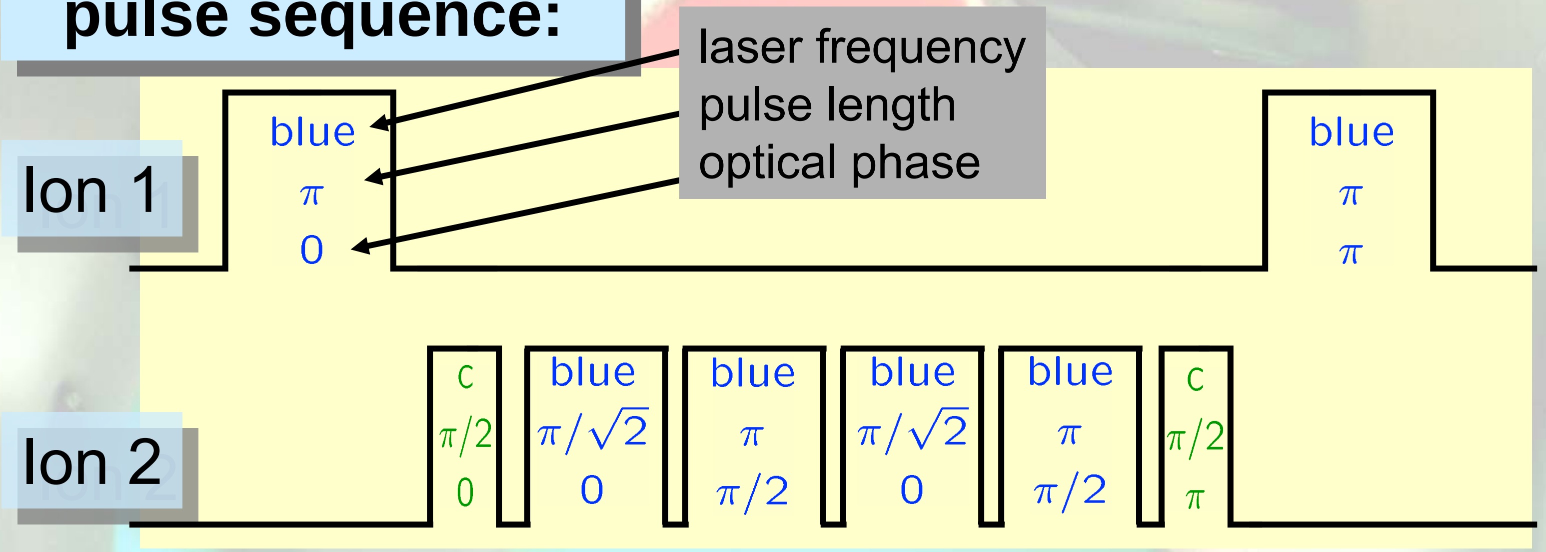
control bit target bit

F. Schmidt-Kaler et al., Nature **422**, 408 (2003)

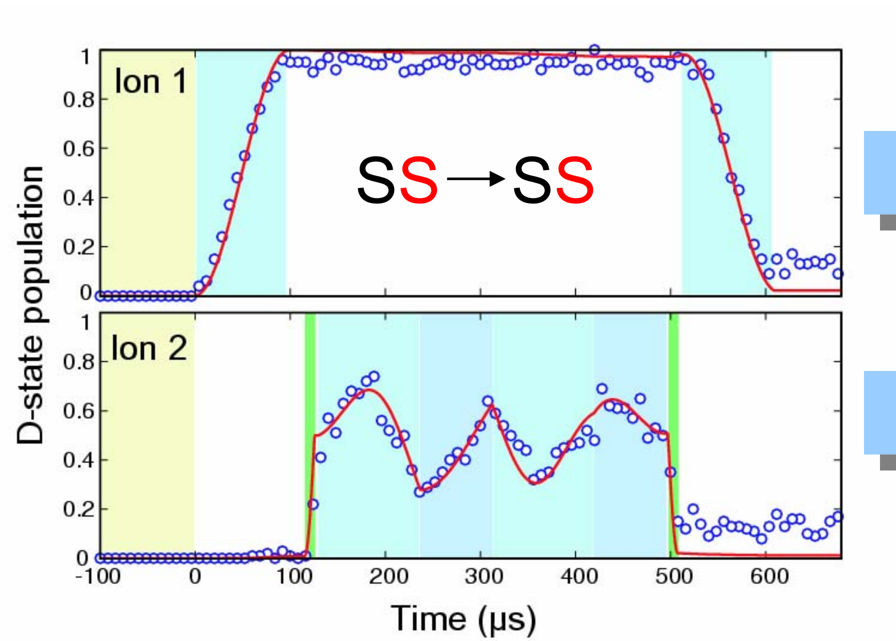
Cirac - Zoller two-ion controlled-NOT operation



pulse sequence:

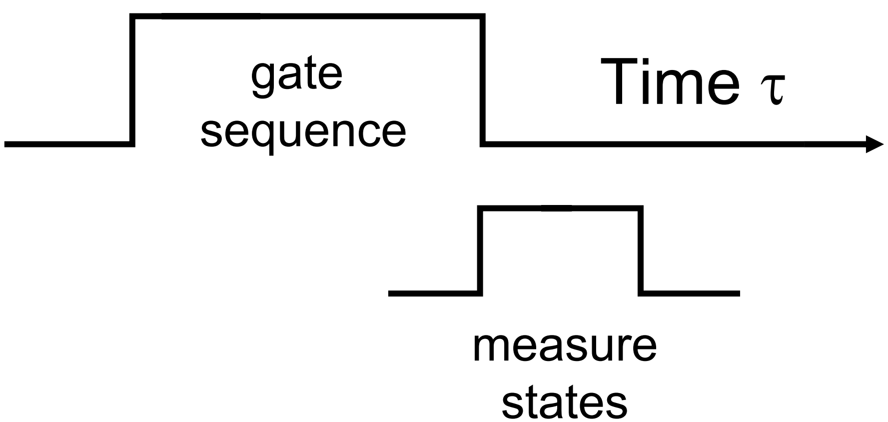


Individual ion detection



control qubit

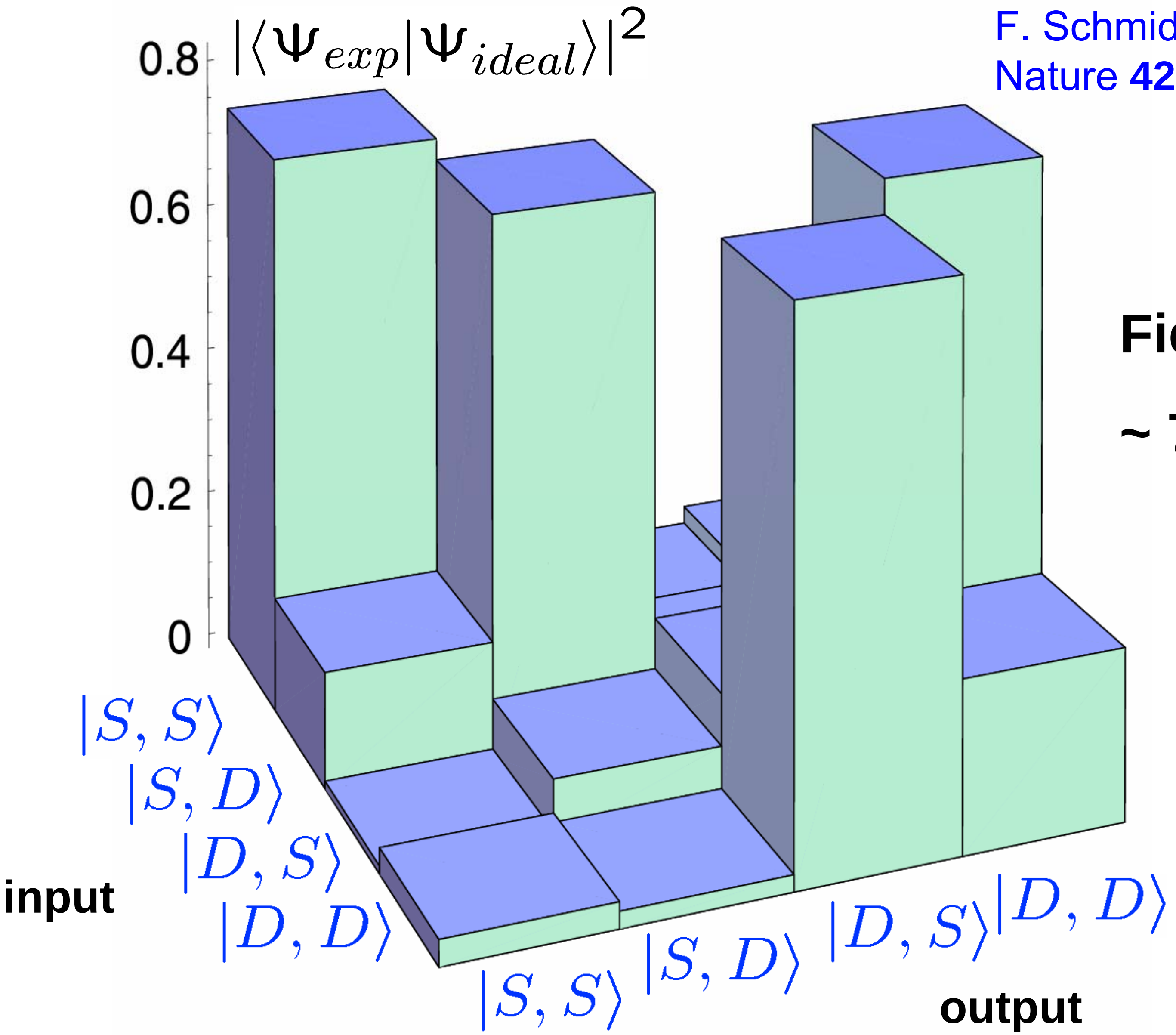
target qubit



Ion 1 Ion 2

Individual ion detection on CCD camera

Experimental fidelity of Cirac-Zoller CNOT operation



F. Schmidt-Kaler et al., Nature **422**, 408 (2003)

Fidelity

~ 71(3) %

CNOT error budget (November 2002)

Error source	Magnitude	Fidelity loss
Frequency noise (fast)	< 200 Hz (FWHM)	< 10 %
Frequency noise (slow)	~ 450Hz (FWHM)	~ 1 %
Laser intensity noise	3 % peak to peak	0.1 %
Addressing error (can be corrected for partially)	5 % in Rabi frequency (at neighbouring ion)	3 %
Off resonant excitations	for $t_{gate} = 600$ μs	4 %
Residual thermal excitation	<n>bus < 0.02 <n>spec = 6	< 2 % 0.4 %
Total	November 2002	~ 20 %

Improvements since then

Technical improvements:

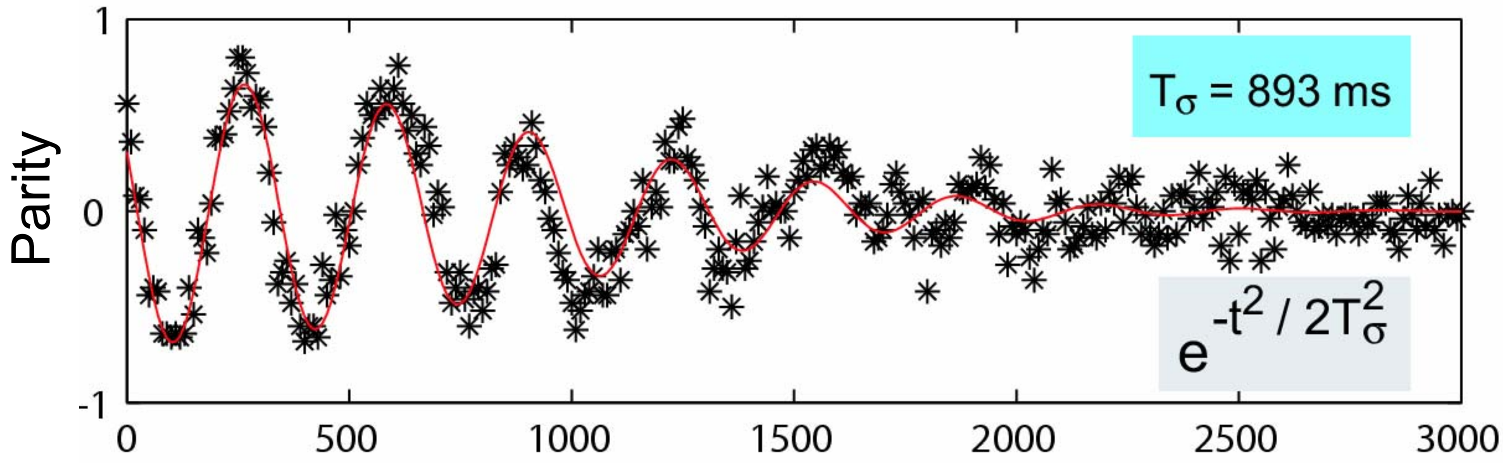
- Laser frequency stability (729 nm)
- Reduced magnetic field noise
- Addressing error correction
- Pulse shaping of composite pulses
- Frequency selective optical pumping
- Automatic calibration and experimental control

Physical improvements:

- Encoding in decoherence free subspace
- Encoding of different qubit ($^{43}Ca^{+}$)
- Tomography for analysis

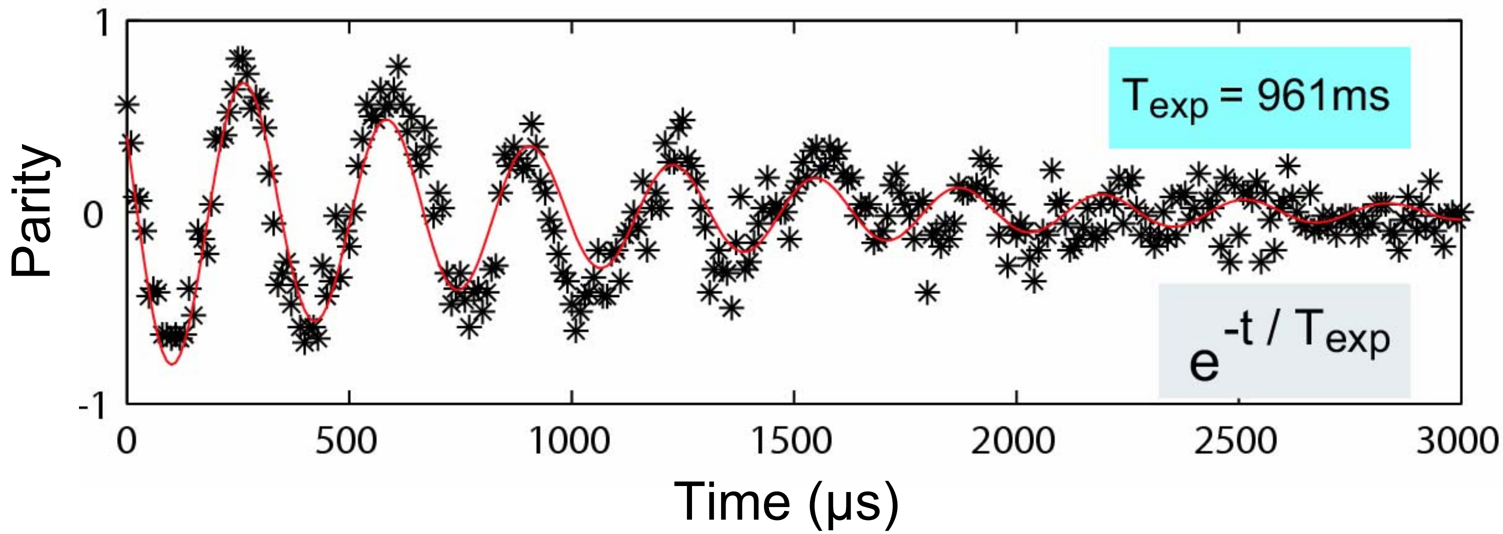
Linewidth of 729 nm laser

Parity measurement for state: $|SS'\rangle + |DD'\rangle$



Gaussian fit

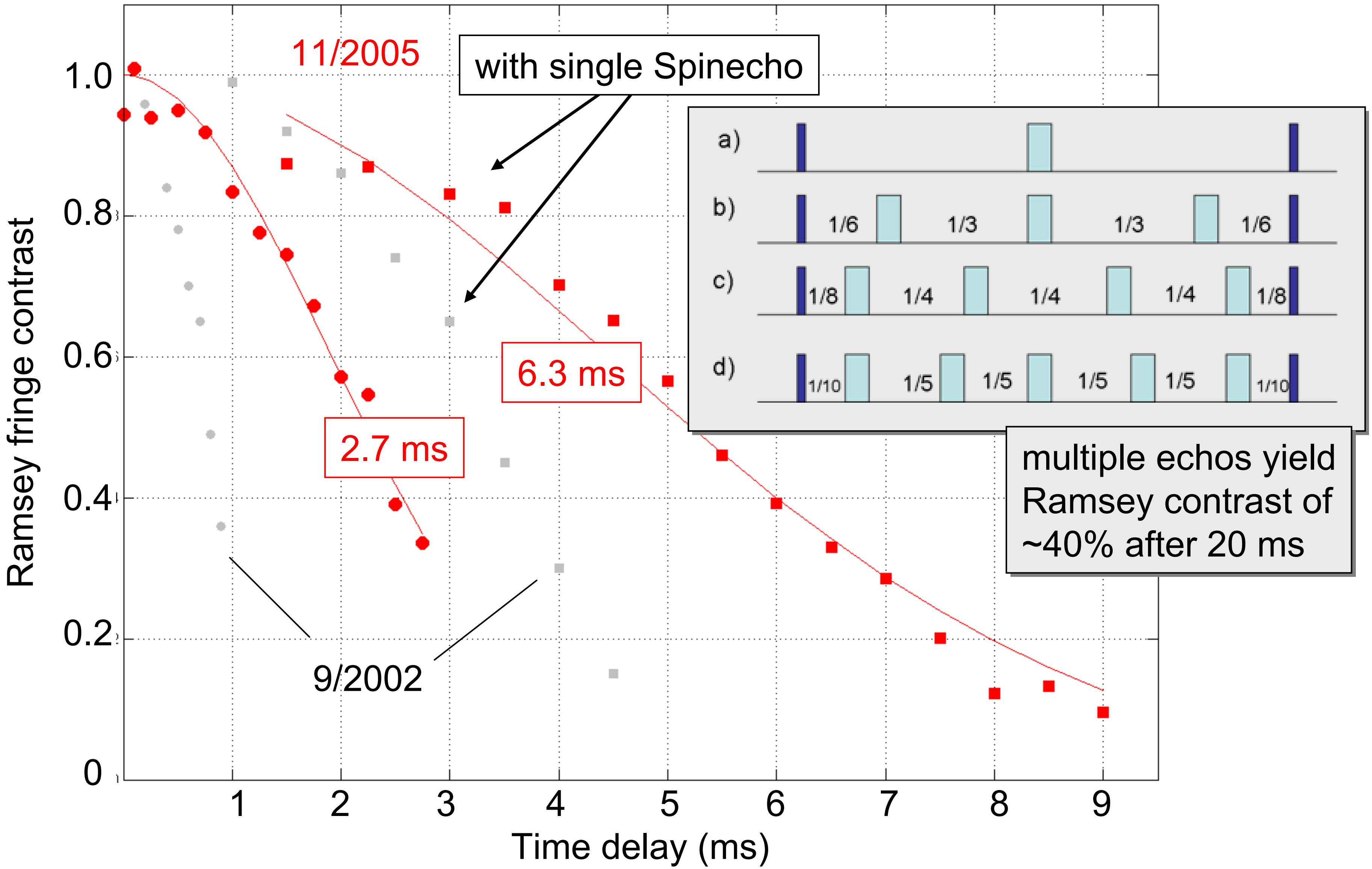
$178\ Hz$



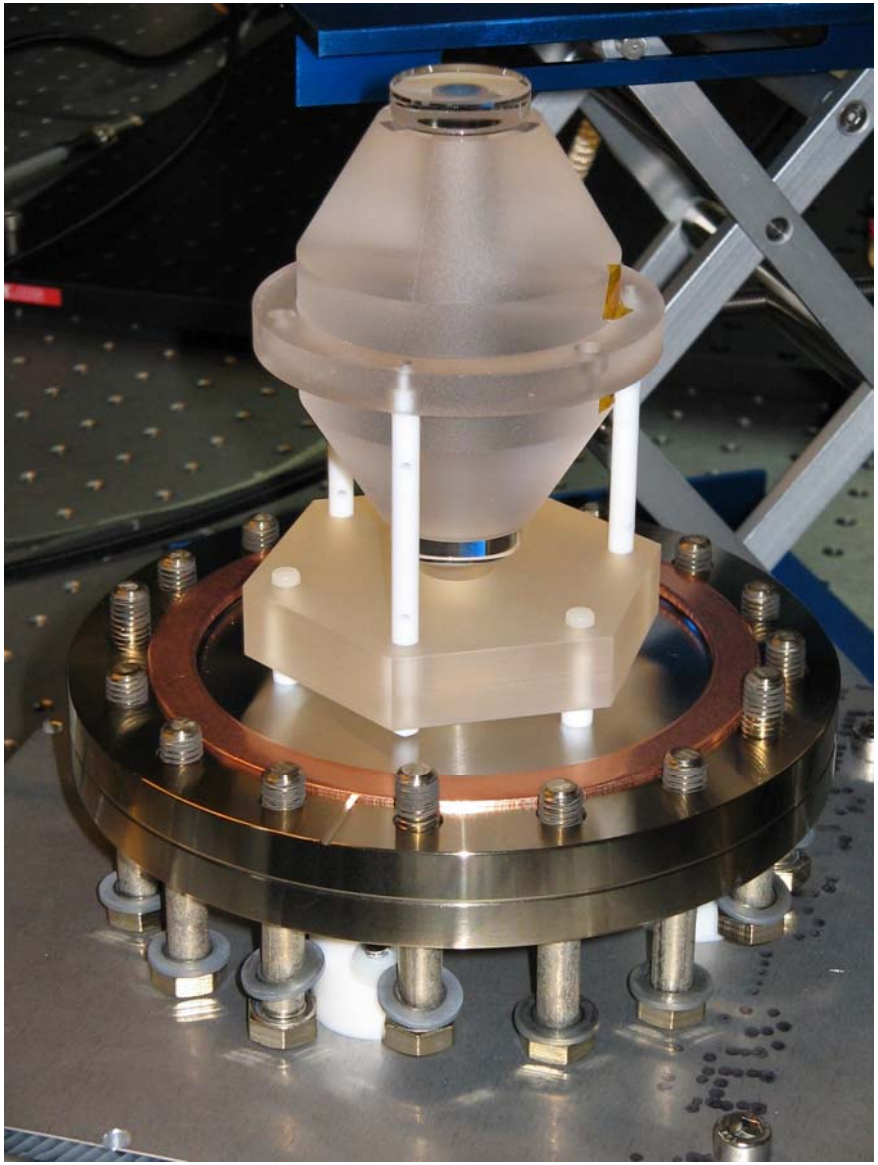
exponential fit

$166\ Hz$

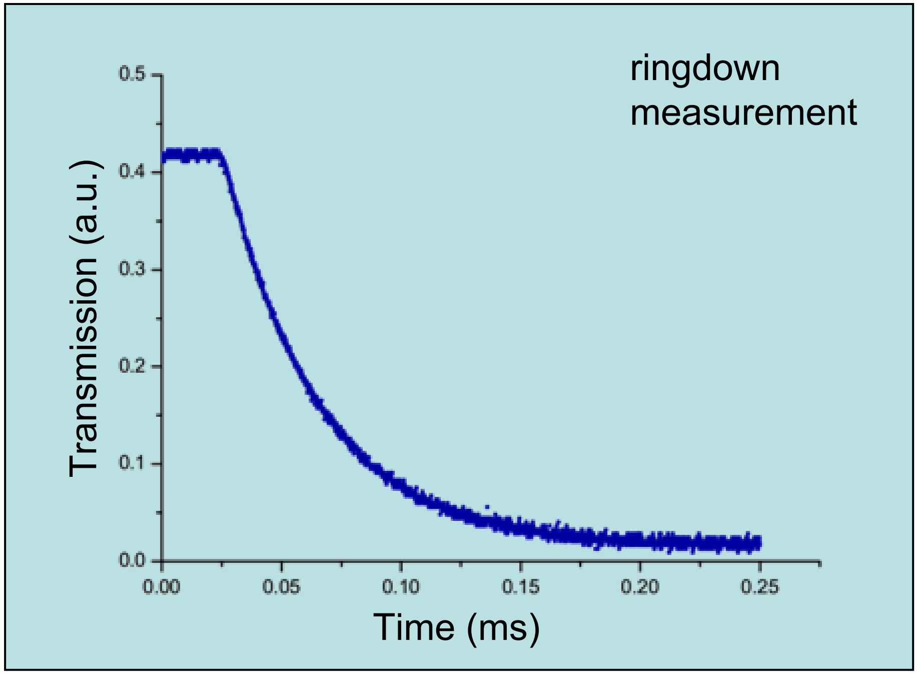
Coherence of single qubits (S – D transition)



New supercavity for 729 nm laser



Vertically mounted high finesse cavity
(Jun Ye, Mark Notcutt; JILA)



Finesse = 481 000 (4000)

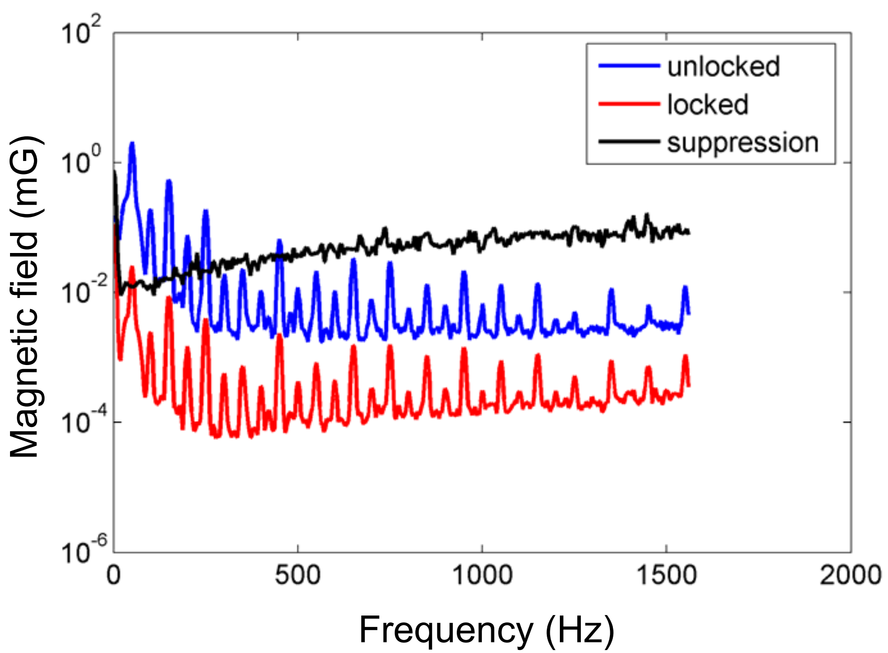
Magnetic field noise (~ frequency fluctuations) 1

without active stabilization:

9mG peak-to-peak @ 50 Hz at the ion,
Ramsey measurement, scanning through the AC-line phase

with active stabilization (Spicer SC12, two AC sensors, 5Hz-20KHz):

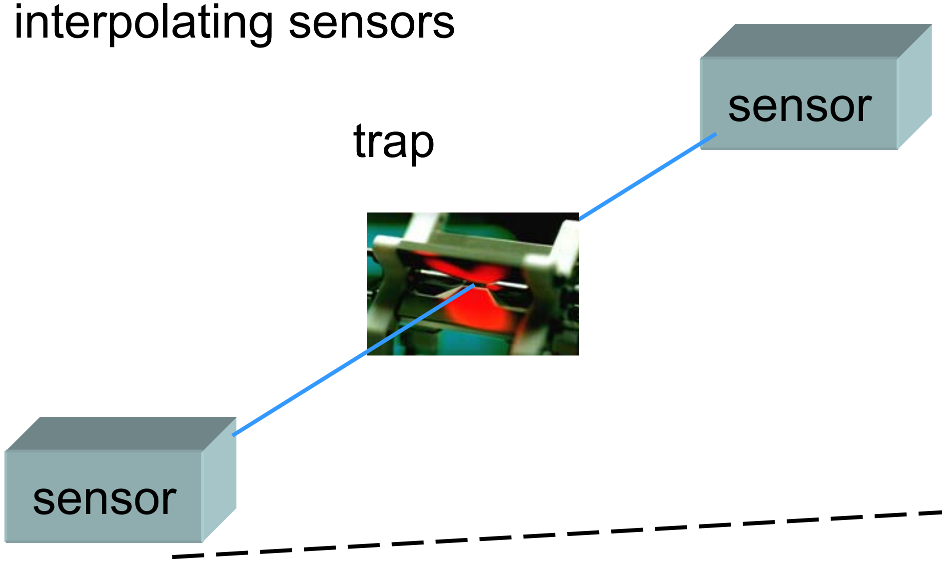
best result 0.4 mG peak-to-peak @ 50 Hz at the ion,
noise suppression of factor ~20
at site of one of the sensors much higher suppression:

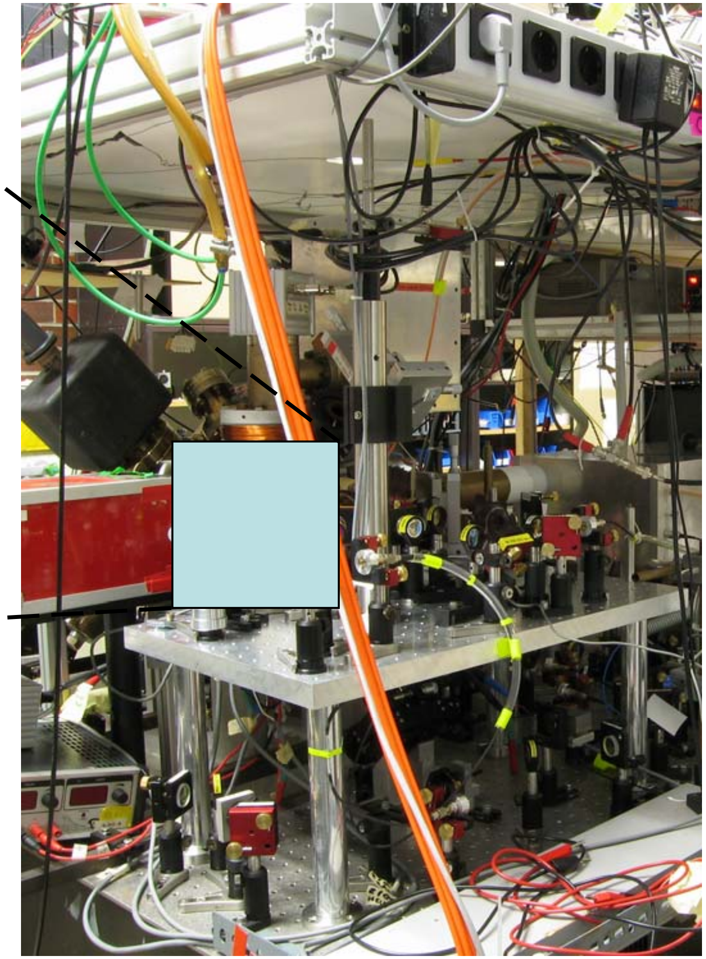


- spectrum contains components that are not multiples of the line frequency,
- cannot eliminate this noise completely by triggering our experiment to the line phase

Magnetic field noise (~ frequency fluctuations) 2

noise cancellation using
interpolating sensors



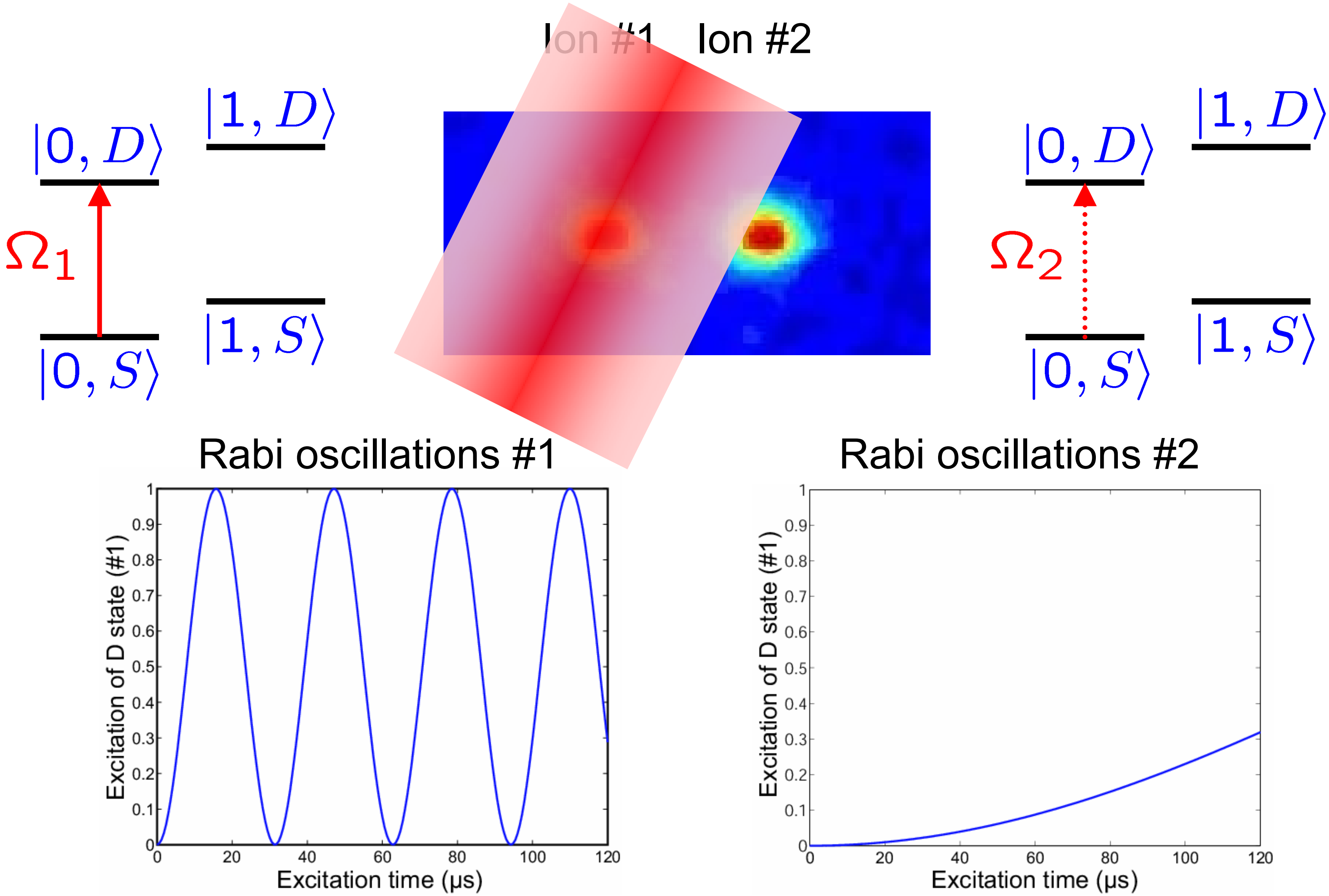


Higher-order gradients prevent the two-sensor system from reaching its full potential;

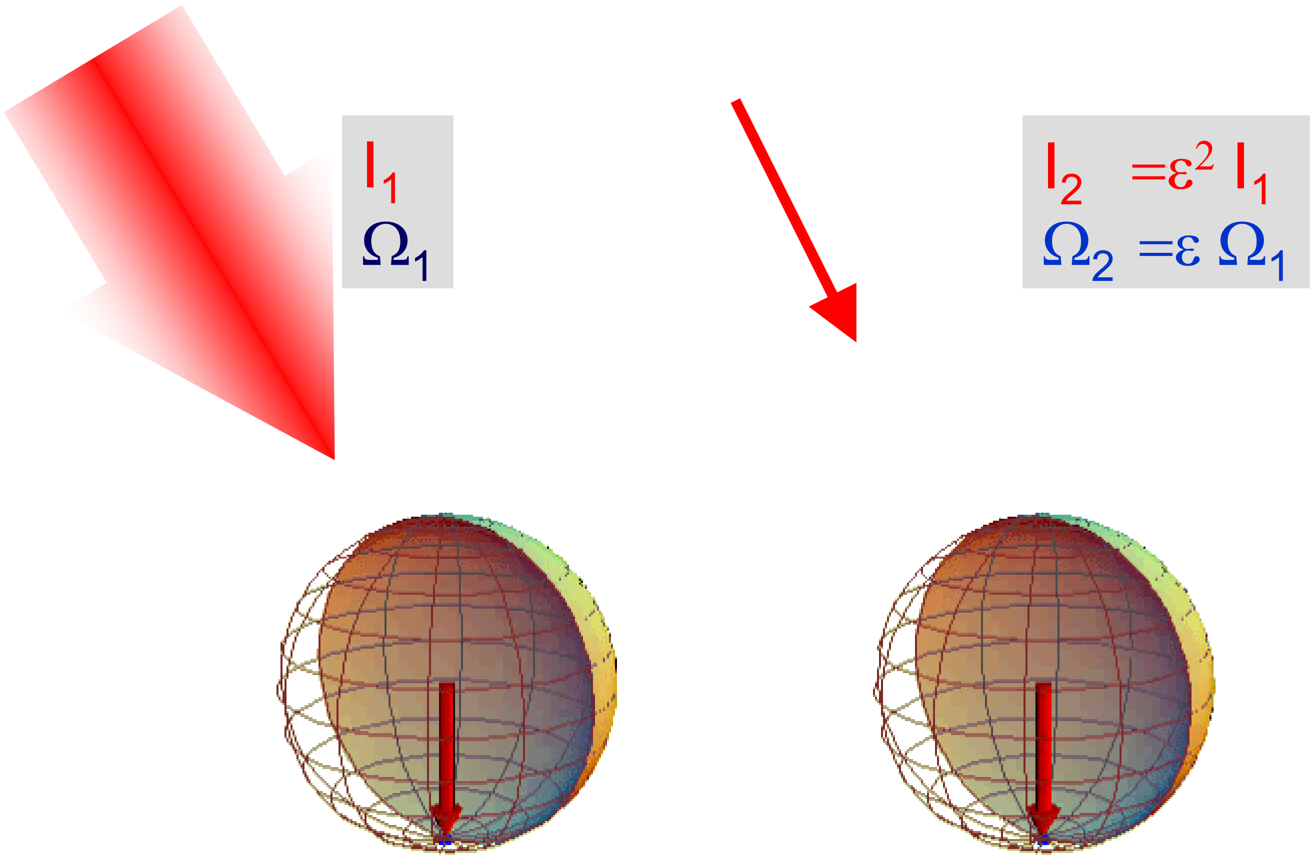
field lines may get warped by vacuum chamber (needs to be investigated), nearby components and by field coils

→ **μ - metal shielding ?**

Addressing error of individual ions

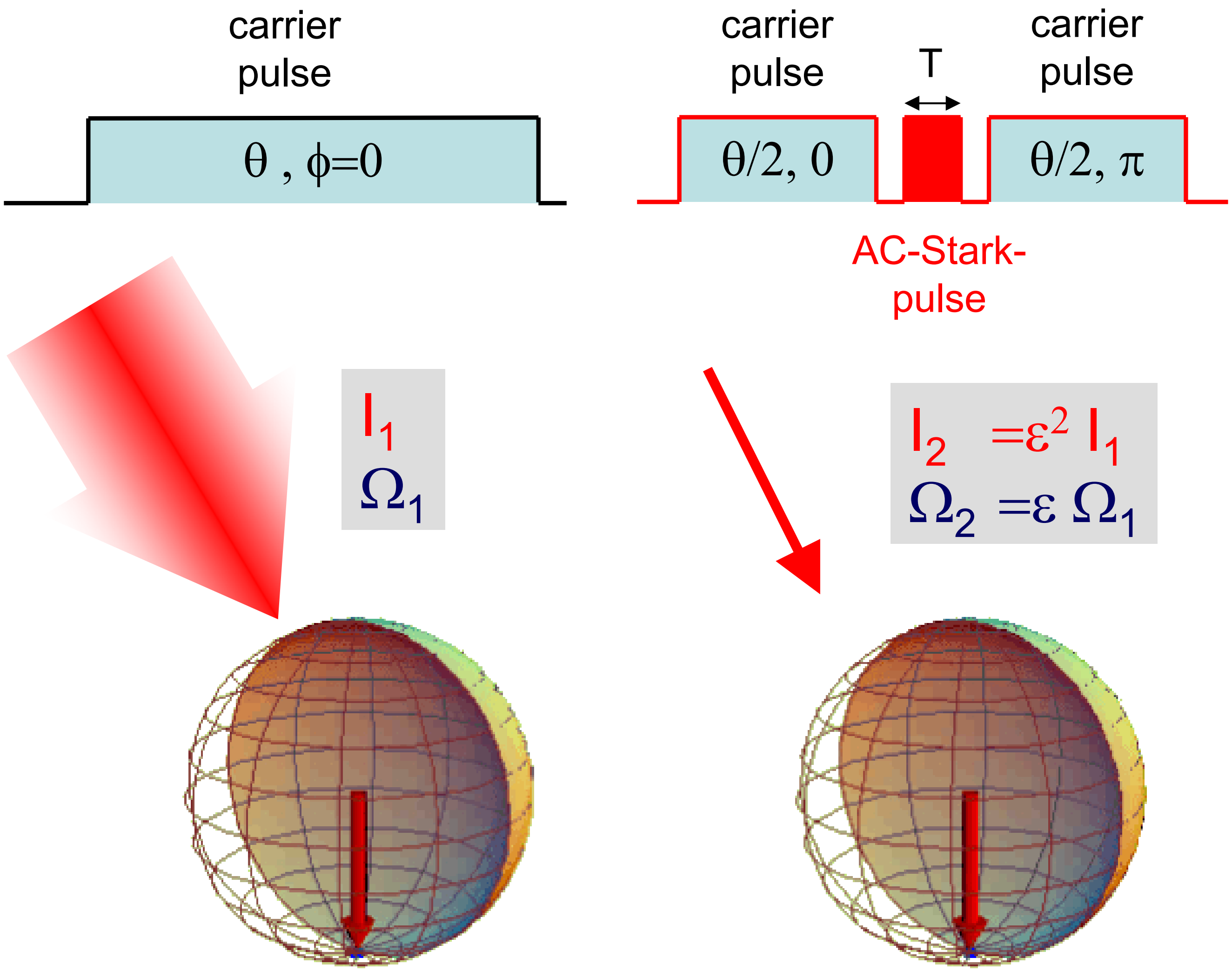


Addressing error



example: ε = 50%

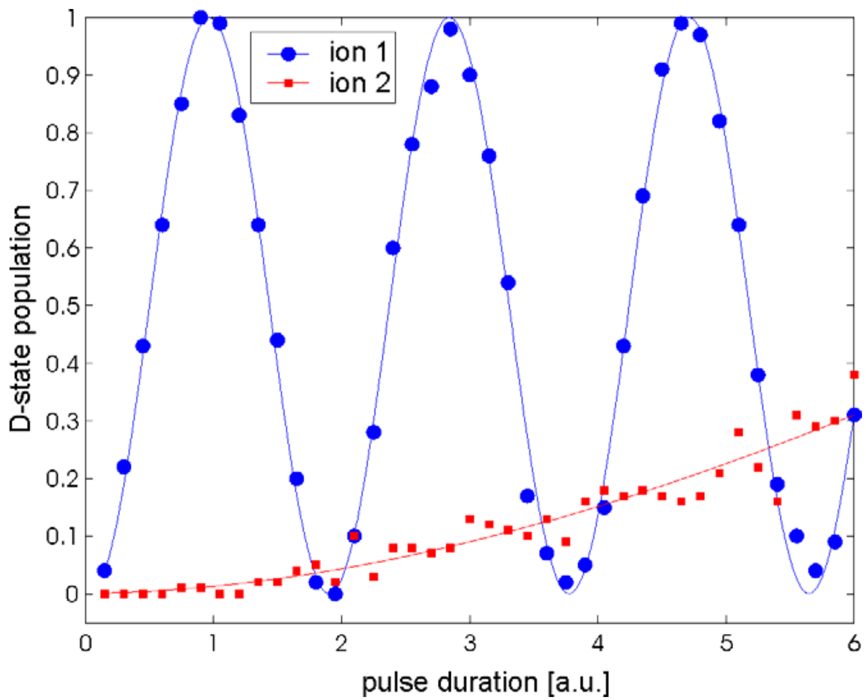
Correction of the addressing error



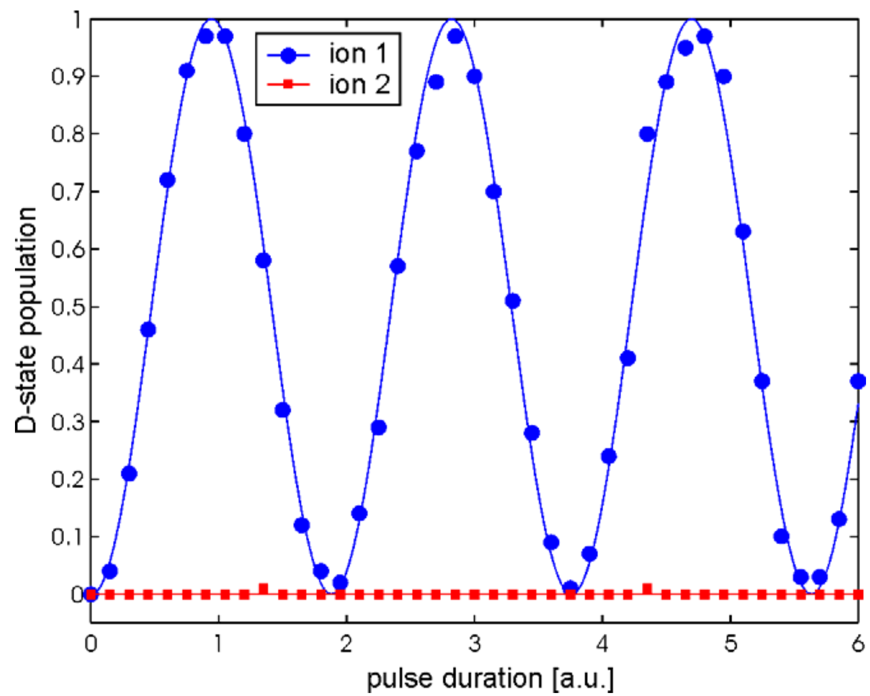
example: ε = 50%

Addressing error correction (November 2005)

$\varepsilon_{\text{add}} = 5.7\%$



$\varepsilon_{\text{add}} < 1\%$

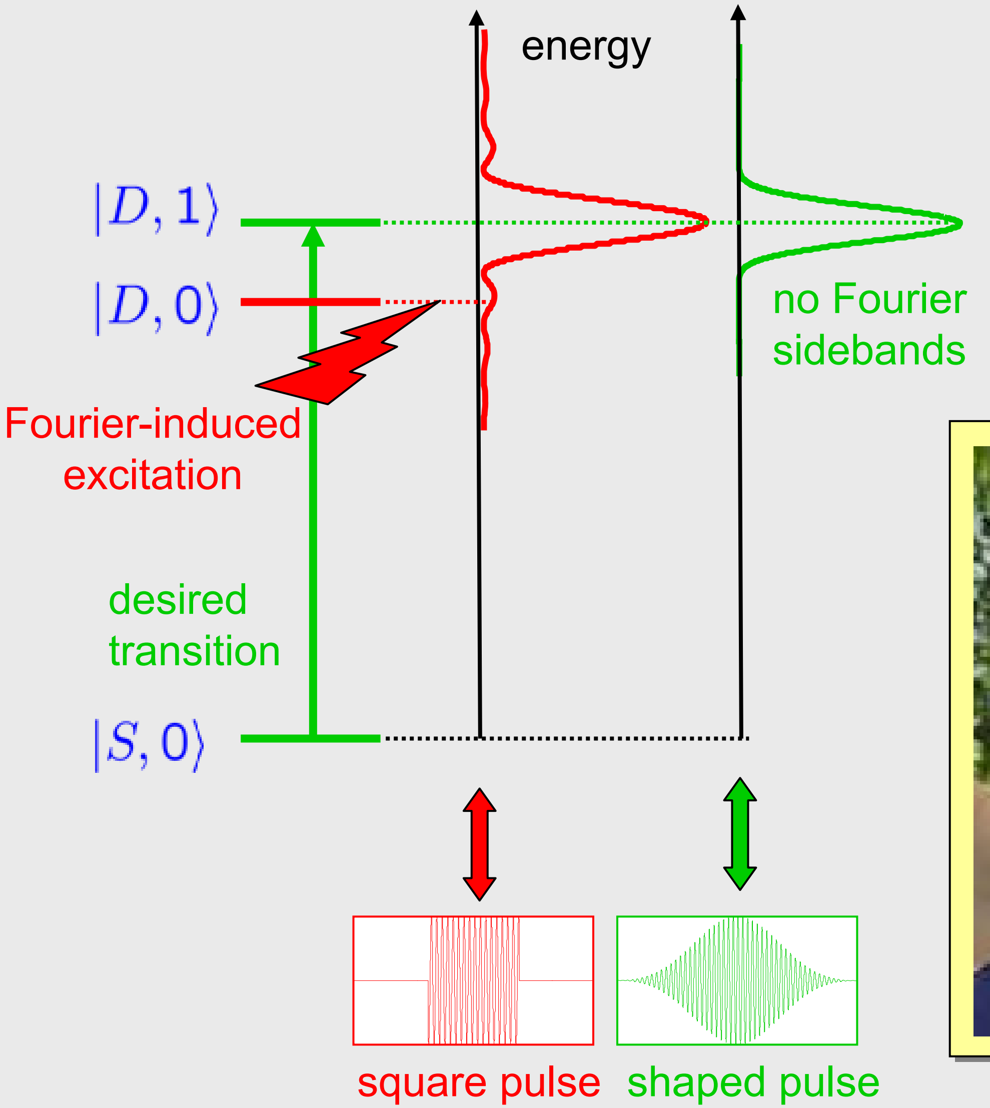


$$\varepsilon_{\text{add}} = \frac{\Omega_{\text{not addressed}}}{\Omega_{\text{addressed}}}$$

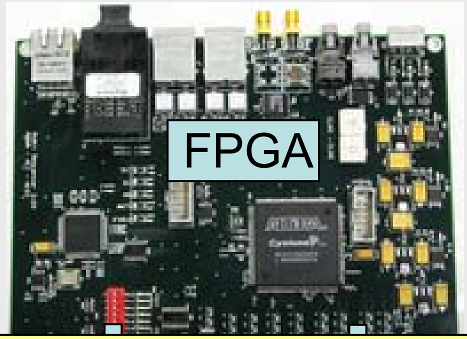
Correction possible to much better than

1% residual error on neighbouring ion

Pulse shaping for improved state manipulation



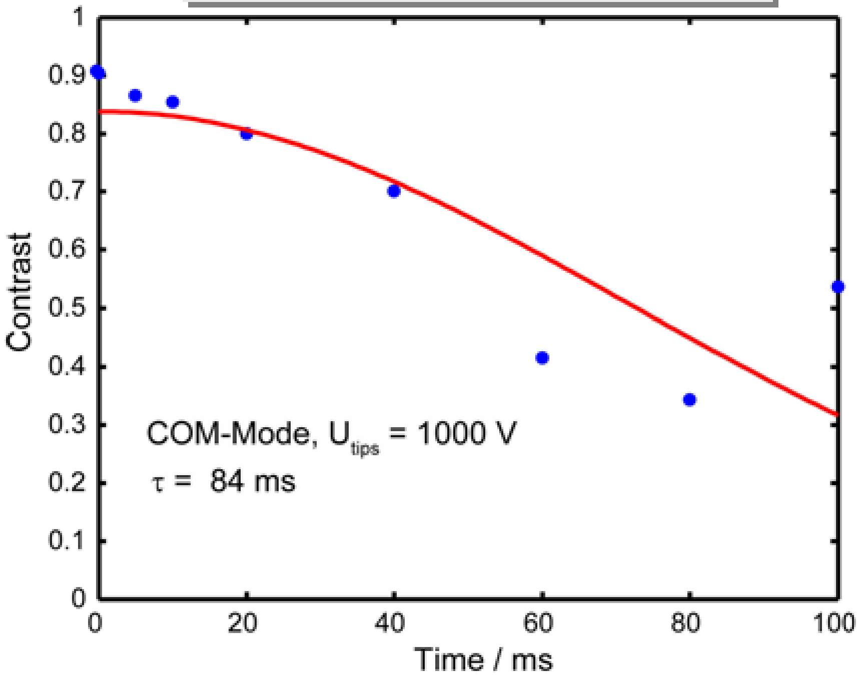
Development of versatile RF source:



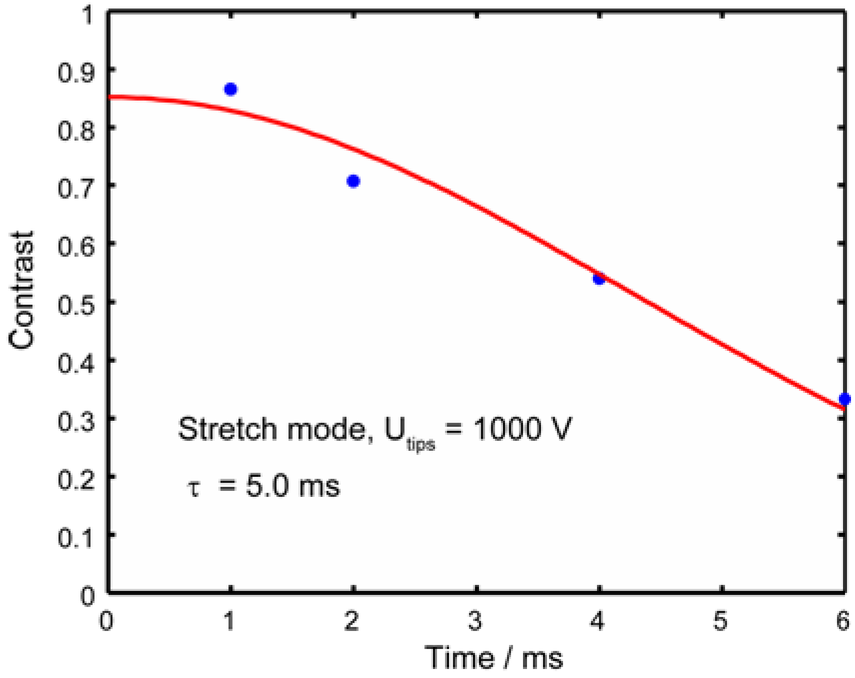
Paul Pham, Ike Chuang (MIT)

Motional decoherence, COM and stretch mode

COM mode



Stretch mode



$\tau = 84\ ms$

$\tau = 5\ ms$?

but….: heating times are similar ~ 100 ms/phonon

Heating time of stretch mode in 2-ion crystal

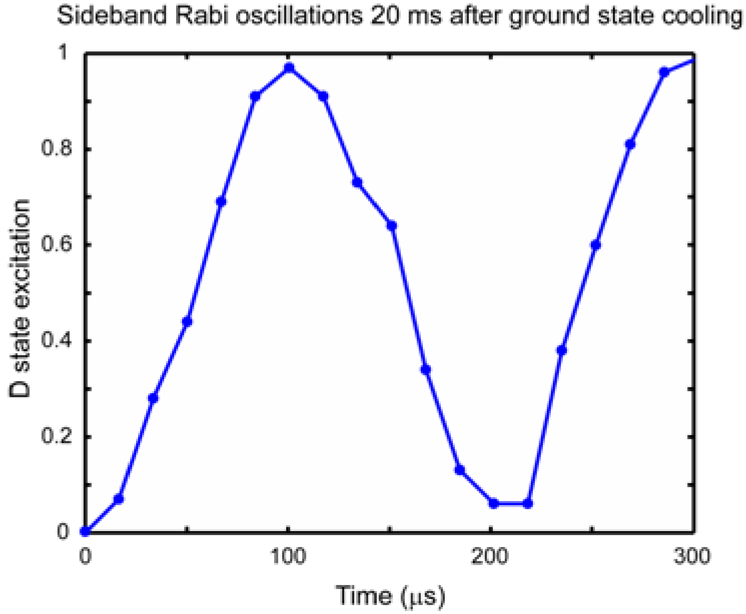
The motional heating rate of the stretch mode is much lower than the dephasing rate:

Experiment:

1. Prepare motional ground state
2. wait 20 ms
3. Drive Rabi oscillations on blue stretch mode sideband

Vibrational quantum number still close to n=0.

U_{tips}=1000 V

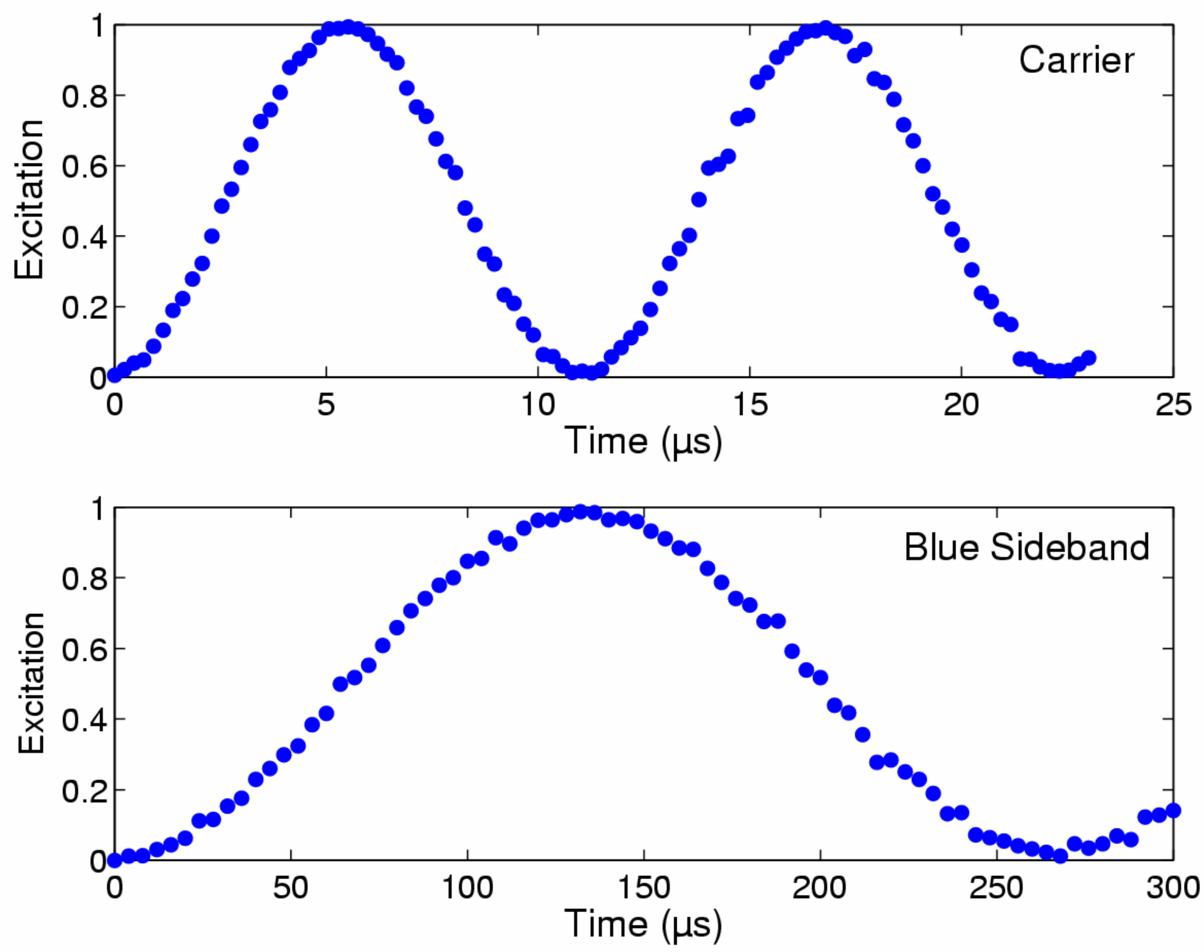


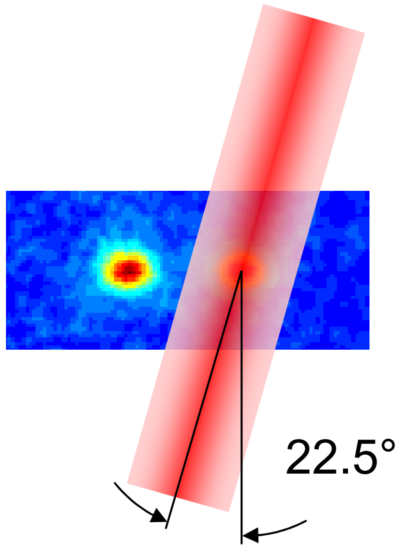
Work towards improved gate operations

- addressing errors:
  avoid using composite pulses ✓
- off-resonant excitations:
  avoid using shaped pulses ✓
- magnetic field fluctuations:
  minimize using active stabilization ✓
- laser frequency noise:
  minimize using improved stabilization **partially implemented**
- fiber phase noise:
  avoid using fiber noise cancellation ✓

Rabi oscillations

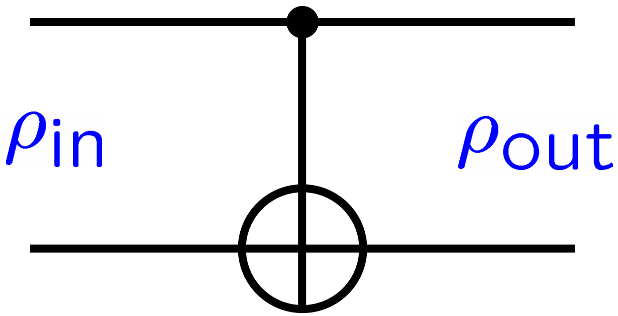
Rabi oscillations of a single ion within a two-ion string





data points: average of 600 measurements

Quantum Process Tomography



$$\rho_{\text{out}} = \sum \chi_{ij} E_i \rho_{\text{in}} E_j^\dagger$$

$$E_i = A_i \otimes A_j$$

$$A_i \in \{I, \sigma_x, \sigma_y, \sigma_z\}$$

$\boxed{\chi_{ij}}$ characterizes gate operation completely

Quantum Process Tomography

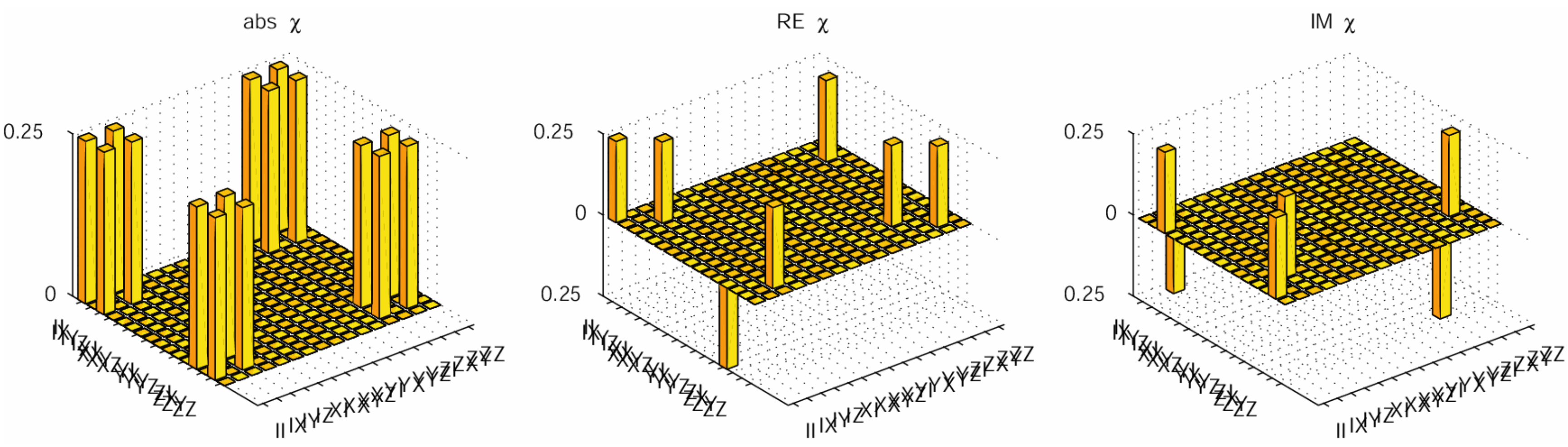
In the basis $\{I, X, Y, Z\} \equiv \{I, \sigma_x, -i\sigma_y, \sigma_z\}$

we obtain

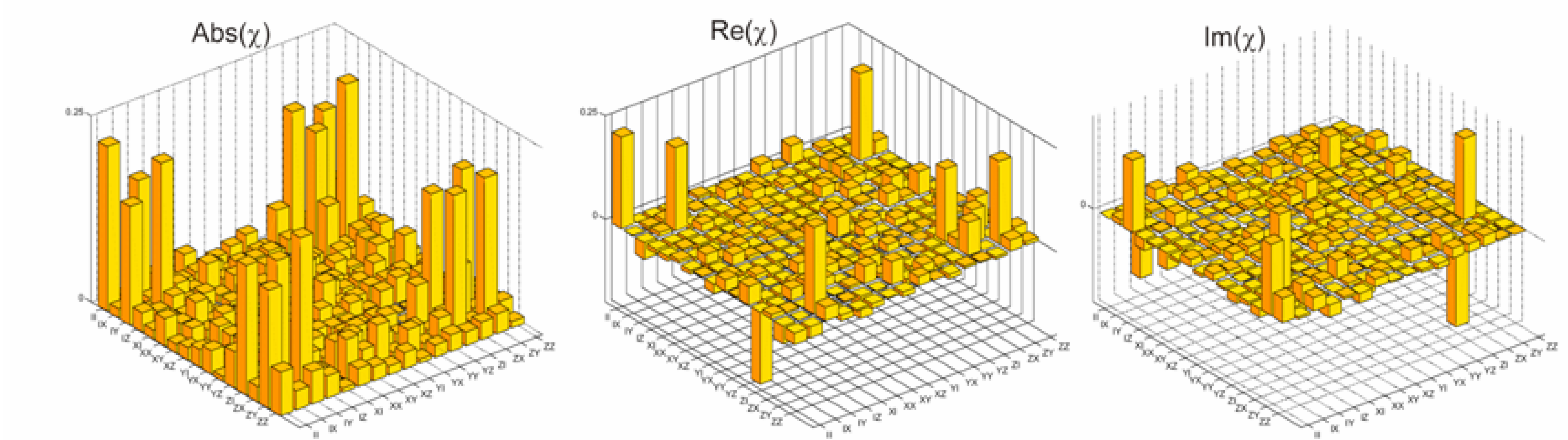
$$U_{\text{CNOT}} = -\frac{1}{2}(I \otimes I + iI \otimes Y - Z \otimes I + iZ \otimes Y)$$

$$= \begin{pmatrix} 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Quantum Process Tomography: CNOT



The transfer matrix χ obtained by quantum process tomography is:



Fidelity: ~ 76%

CNOT error budget (February 2006)

Error source	Magnitude	Fidelity loss
Frequency noise (fast)	< 160 Hz (FWHM)	< 5 %
Frequency noise (slow)	~ 160 Hz (FWHM)	~ 0.6 %
Laser intensity noise	3 % peak to peak	0.1 %
Addressing error (can be corrected for partially)	3 % in Rabi frequency (at neighbouring ion)	1 %
Off resonant excitations	for $t_{gate} = 600\ \mu s$	- (Pulse shaping)
Residual thermal excitation	$\langle n \rangle_{bus} < 0.02$ $\langle n \rangle_{spec} = 6$	< 2 % 0.4 %
Total	February 2006	~ 9 %

Open questions ….

Error modelling → gate fidelity of ~ 90 %

Experiment (gate tomography) → gate fidelity of ~ 75 – 80 %

?

What are we missing ?

What improvements can be done ?

► further technical improvements (laser linewidth, magnetic field)

► yet better measurements, characterization required

► better physical solutions necessary
(less sensitive states, better encoding, error correcting sequences)

→ e.g. decoherence free subspaces (DFS)

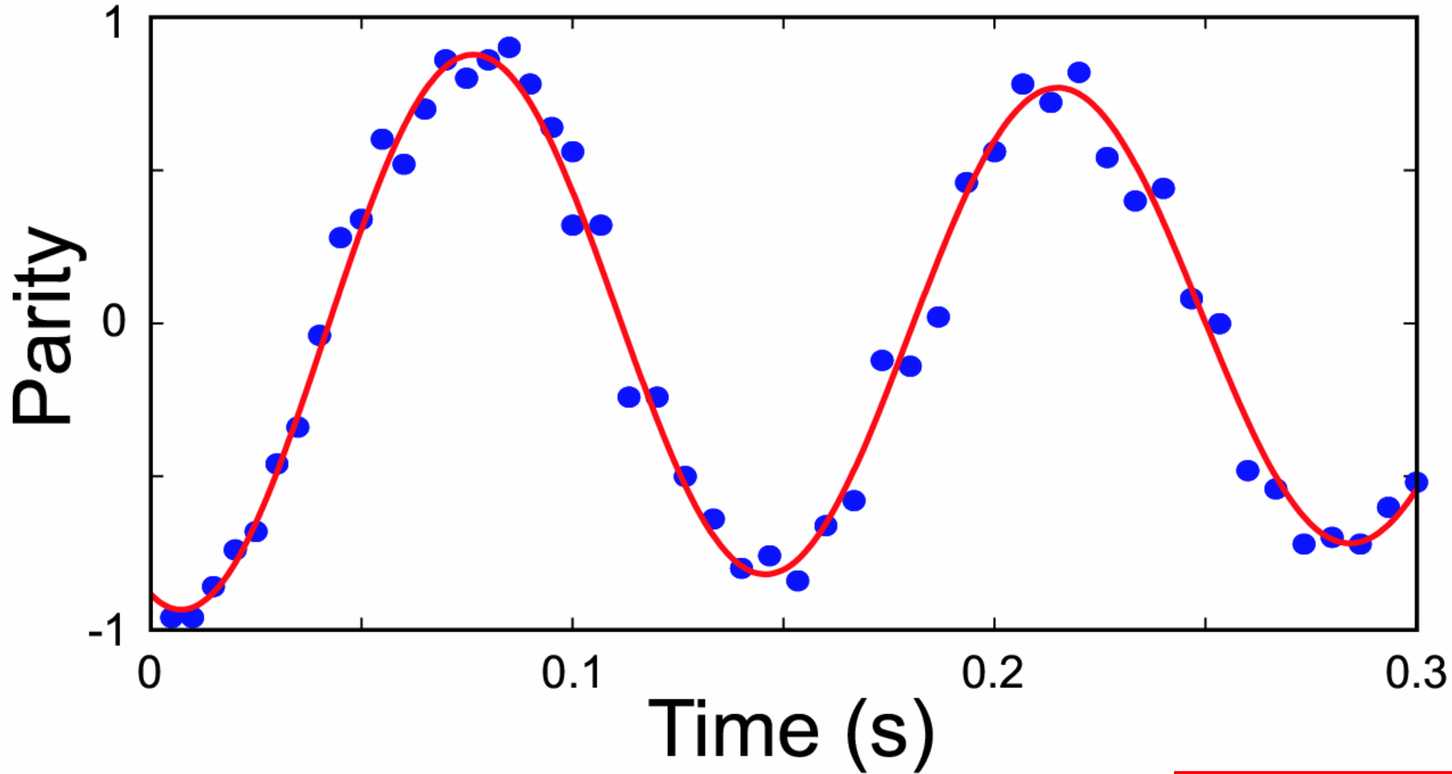
Different Decoherence-free Subspaces (DFS)

DFS: encoding quantum information in superpositions

sensitive to	laser frequency	magnetic field	excited state lifetime
$\|S\rangle + \|D\rangle$	⊗	⊗	⊗
$\|SD\rangle + \|DS\rangle$	○	○	⊗
$\|SS'\rangle + \|S'S\rangle$	○	○	○
$\|SS'\rangle + \|DD'\rangle$	⊗	○	⊗

Decoherence-free Bell states

$$\Psi_- = \frac{1}{\sqrt{2}}(|SD\rangle - |DS\rangle)$$

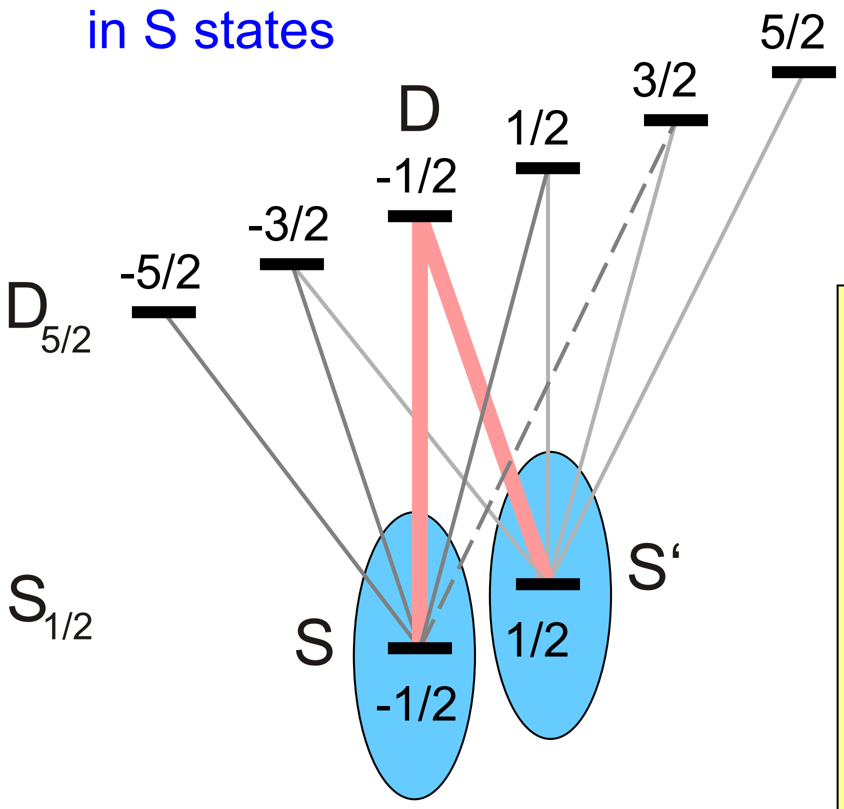


C. Roos et al., Phys. Rev. Lett. **92**, 220402 (2004)

decoherence-time:
0.5 x 1.05(15) s

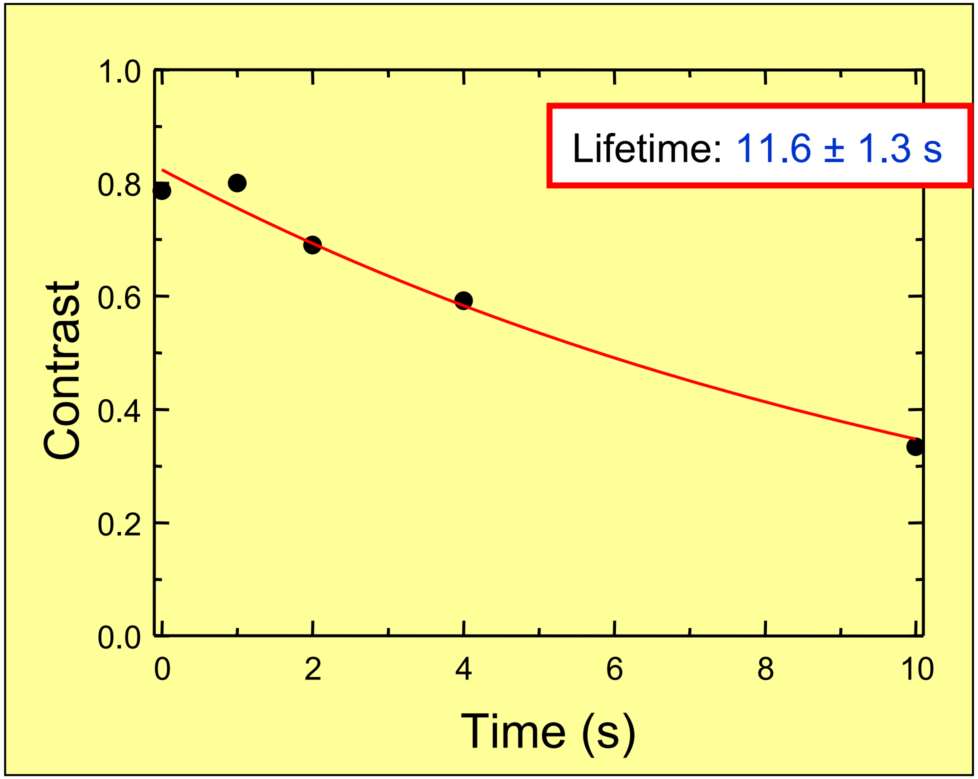
Decoherence-free Bell states

prepare qubits
in S states



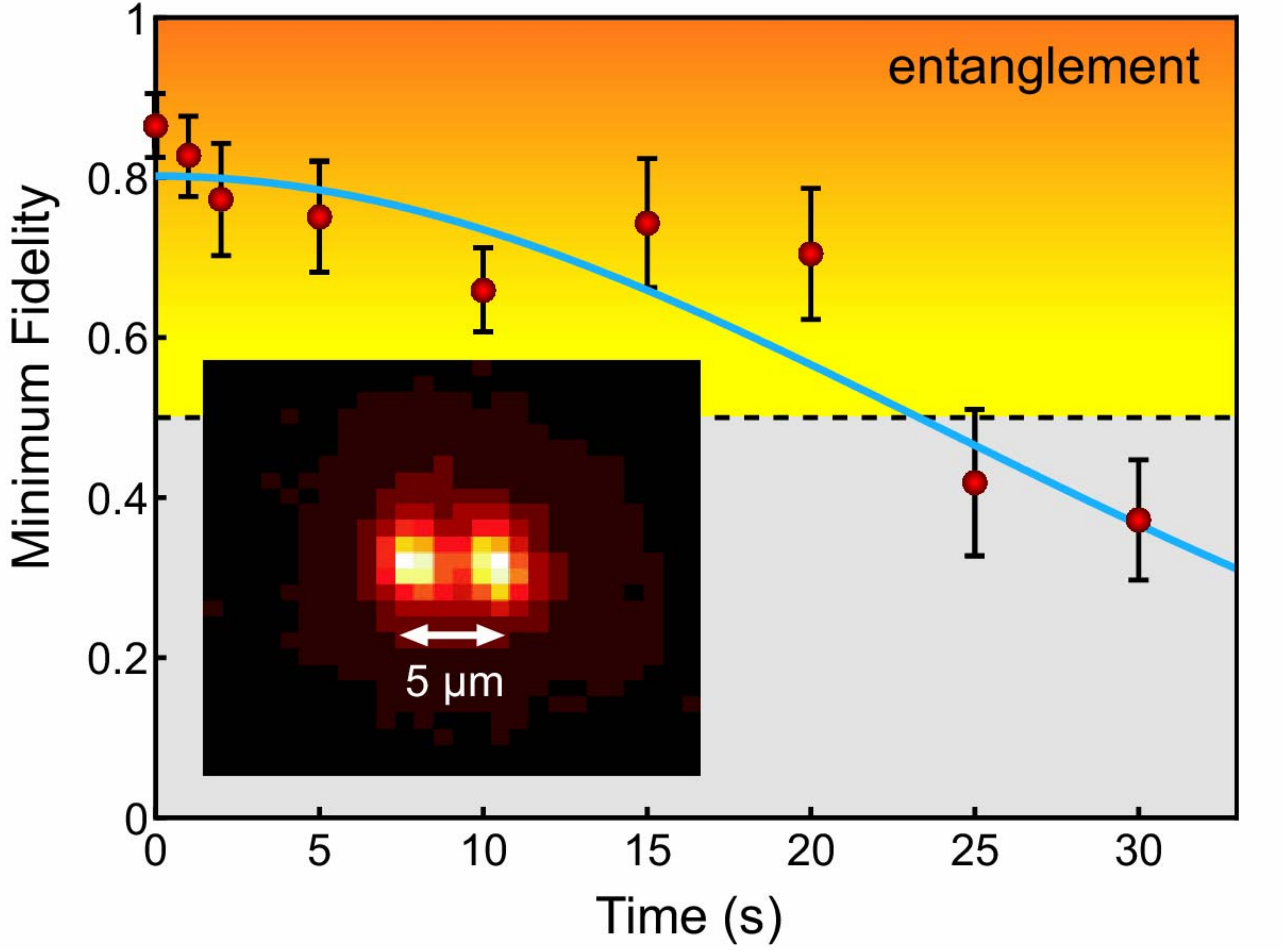
$$\psi = \frac{1}{\sqrt{2}}(|SS'\rangle + e^{i\phi}|S'S\rangle)$$

Hiding states in S, S' states avoids decoherence from spontaneous emission

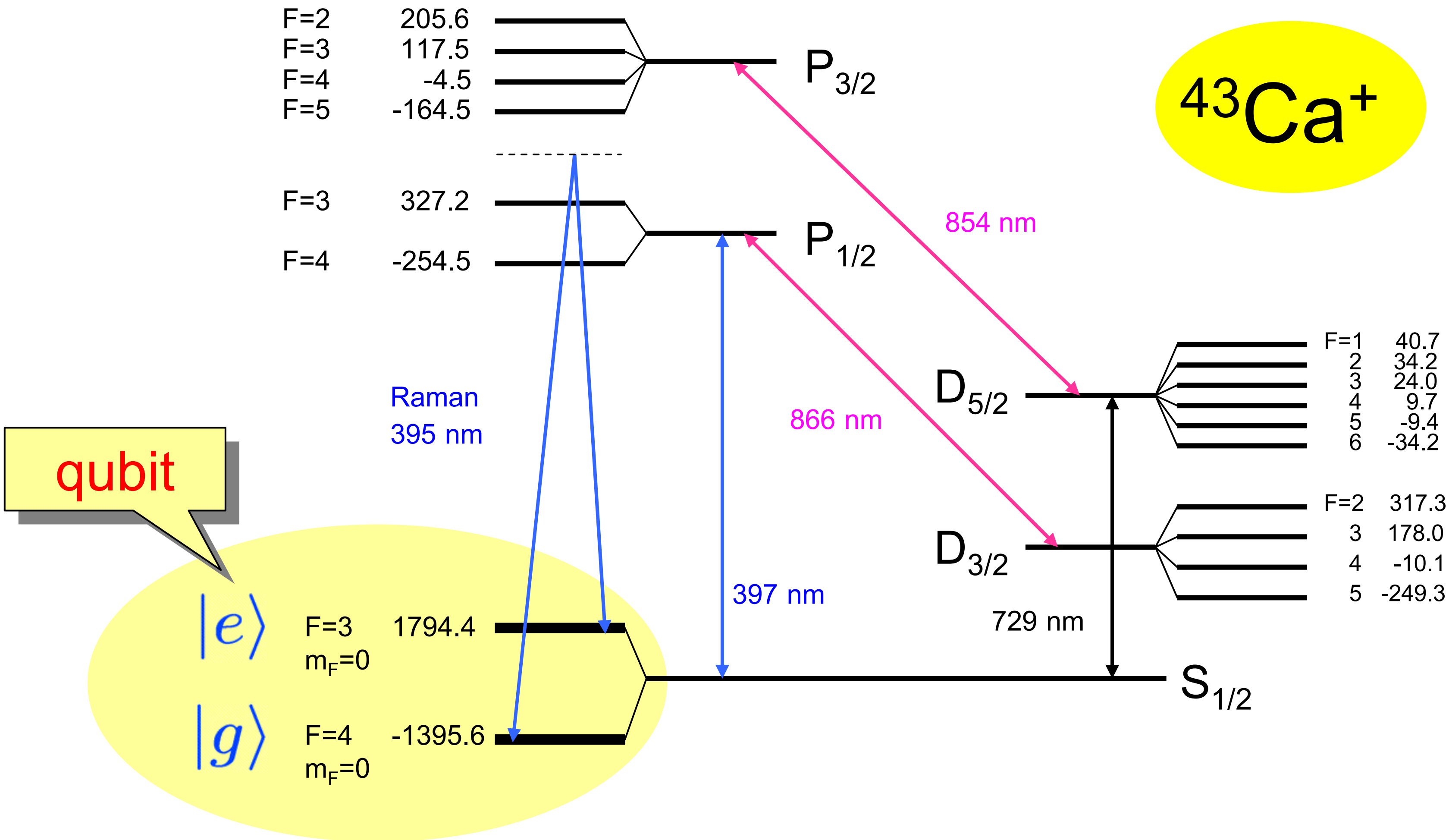


Robust entanglement

H. Häffner et al., Appl. Phys. **B 81**, 151 (2005)



Level scheme of $^{43}Ca^{+}$



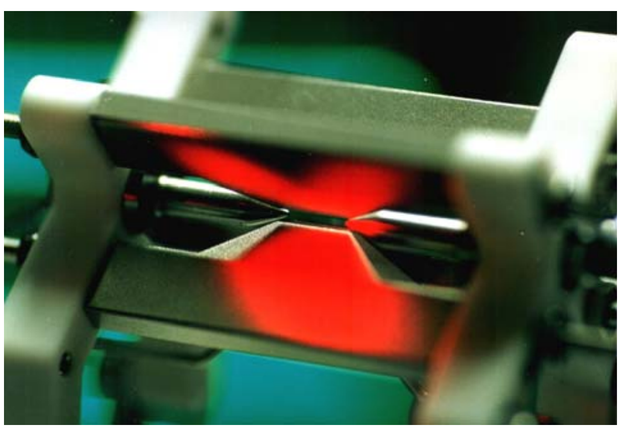
all frequencies in MHz

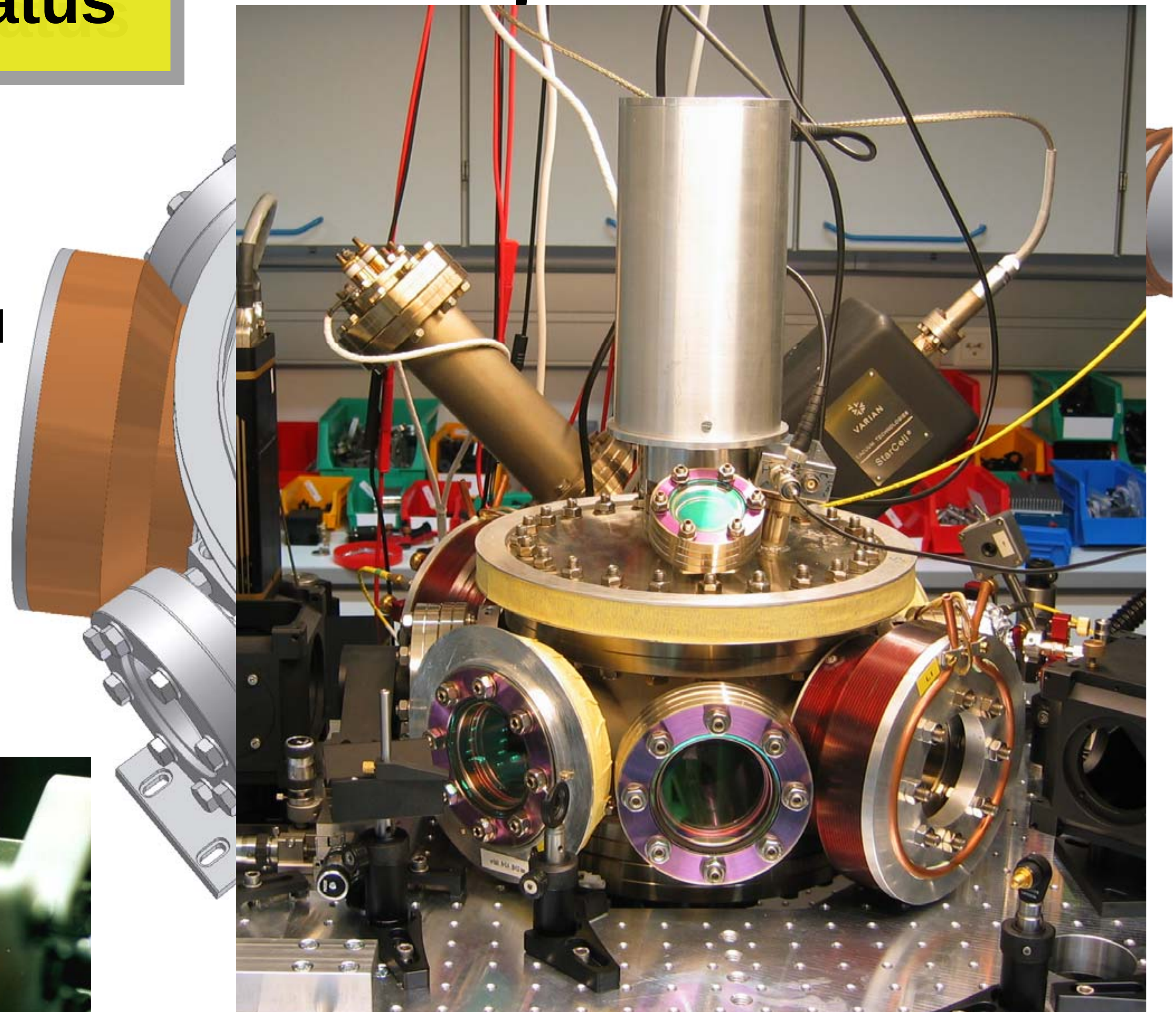
$^{43}Ca^{+}$ Apparatus

Raman

Raman R1, B1

opt.
pumping





Current status of the $^{43}Ca^{+}$ experiment

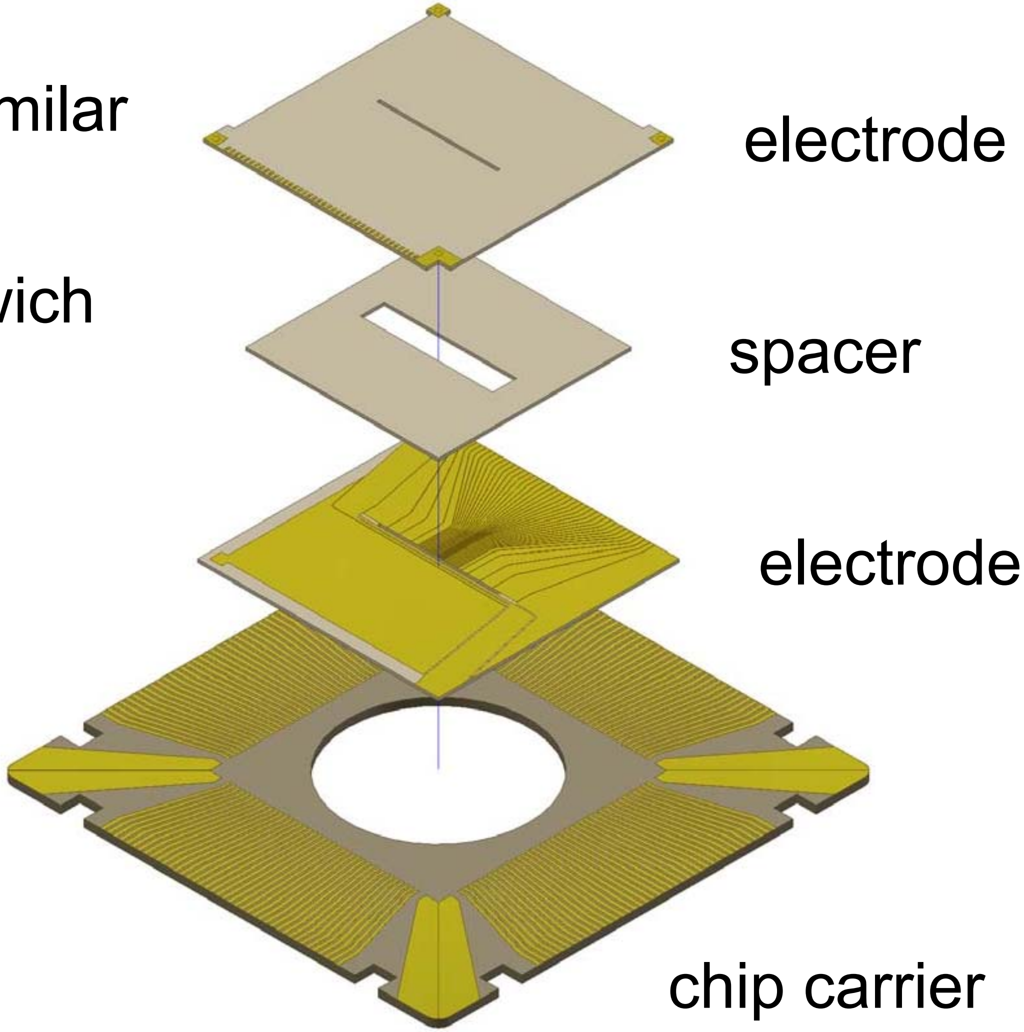
- Detection system completed, ✓
  count rates two times higher than in „old“ $^{40}Ca^{+}$ setup. ✓
- Compensation of micromotion was done ✓
- Photoionization loading of $^{43}Ca^{+}$ works
- Doppler cooling of $^{43}Ca^{+}$, ✓
  Single $^{43}Ca^{+}$ ions, strings of $^{43}Ca^{+}$ ions are routinely prepared
- Setup of shelving laser and Raman laser is finished ✓

Work in progress

- Optimization of laser cooling (the whole spiel)
- Spectroscopy on the shelving transition
- Raman transitions between hyperfine ground states (soon)

Innsbruck segmented trap (2005)

- electrode design similar as in 2004
- assembly as sandwich on chip carrier

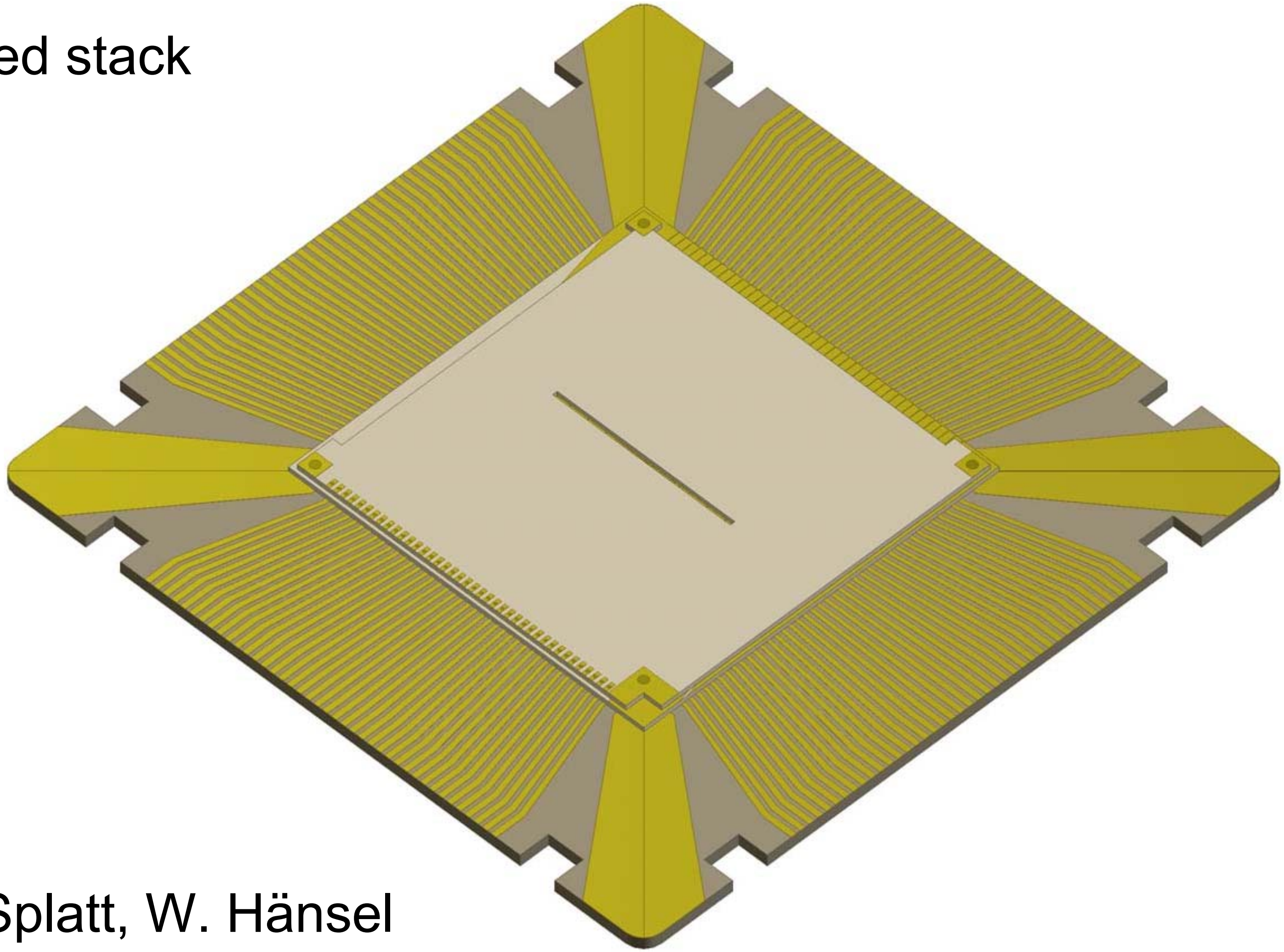


work by

- ► Felicity Splatt
- ► Wolfgang Hänsel

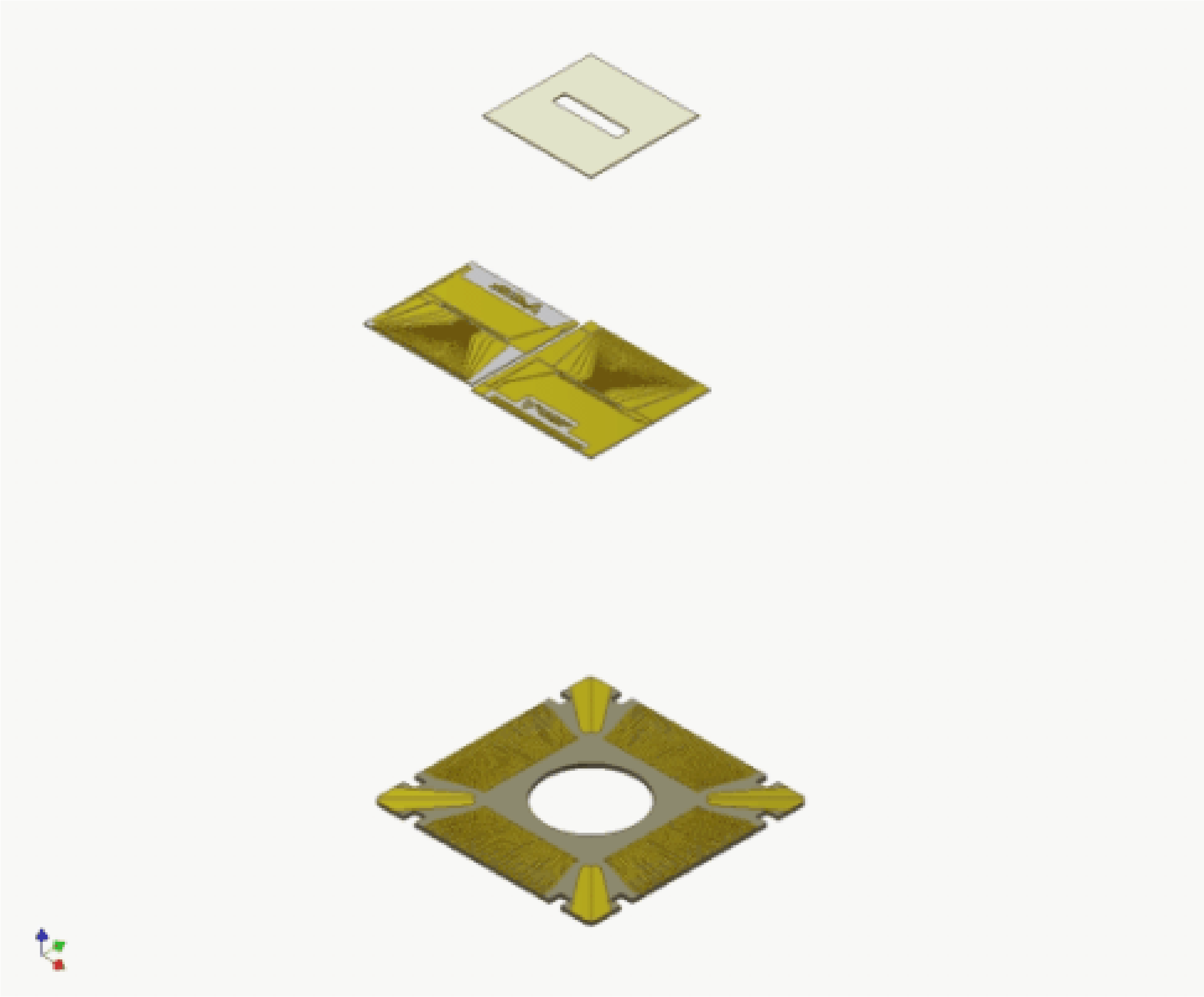
Innsbruck ion chip (2005)

glued stack



F. Splatt, W. Hänsel

Assembly of the chip trap



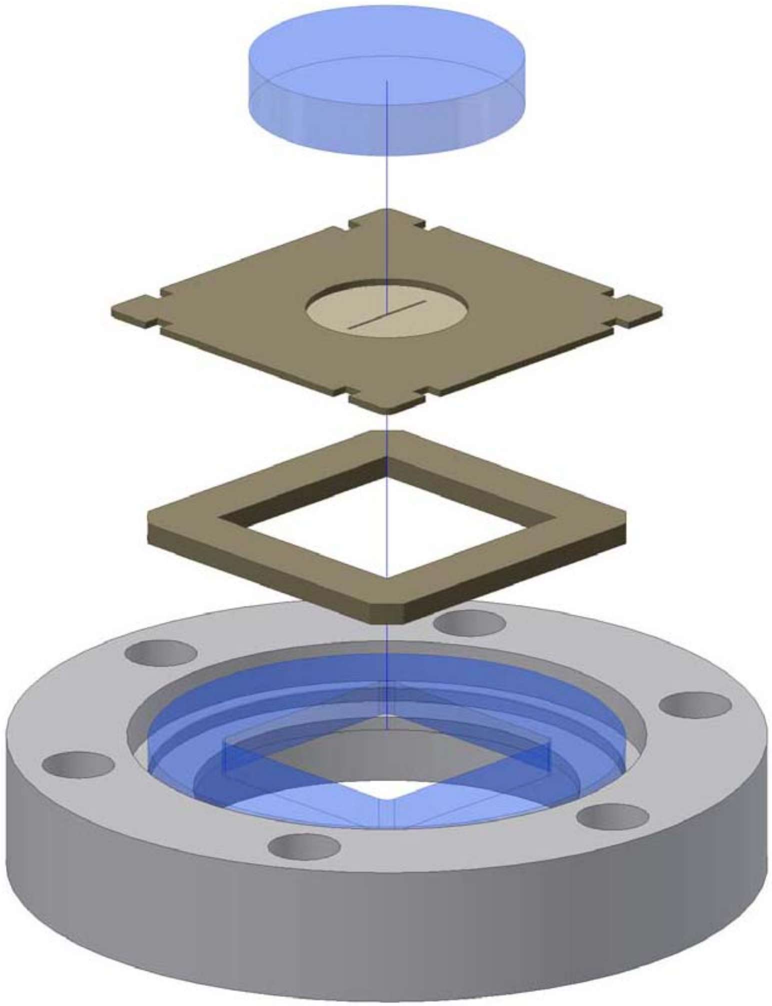
Assembly of Innsbruck ion chip (2005)

top window

ion chip

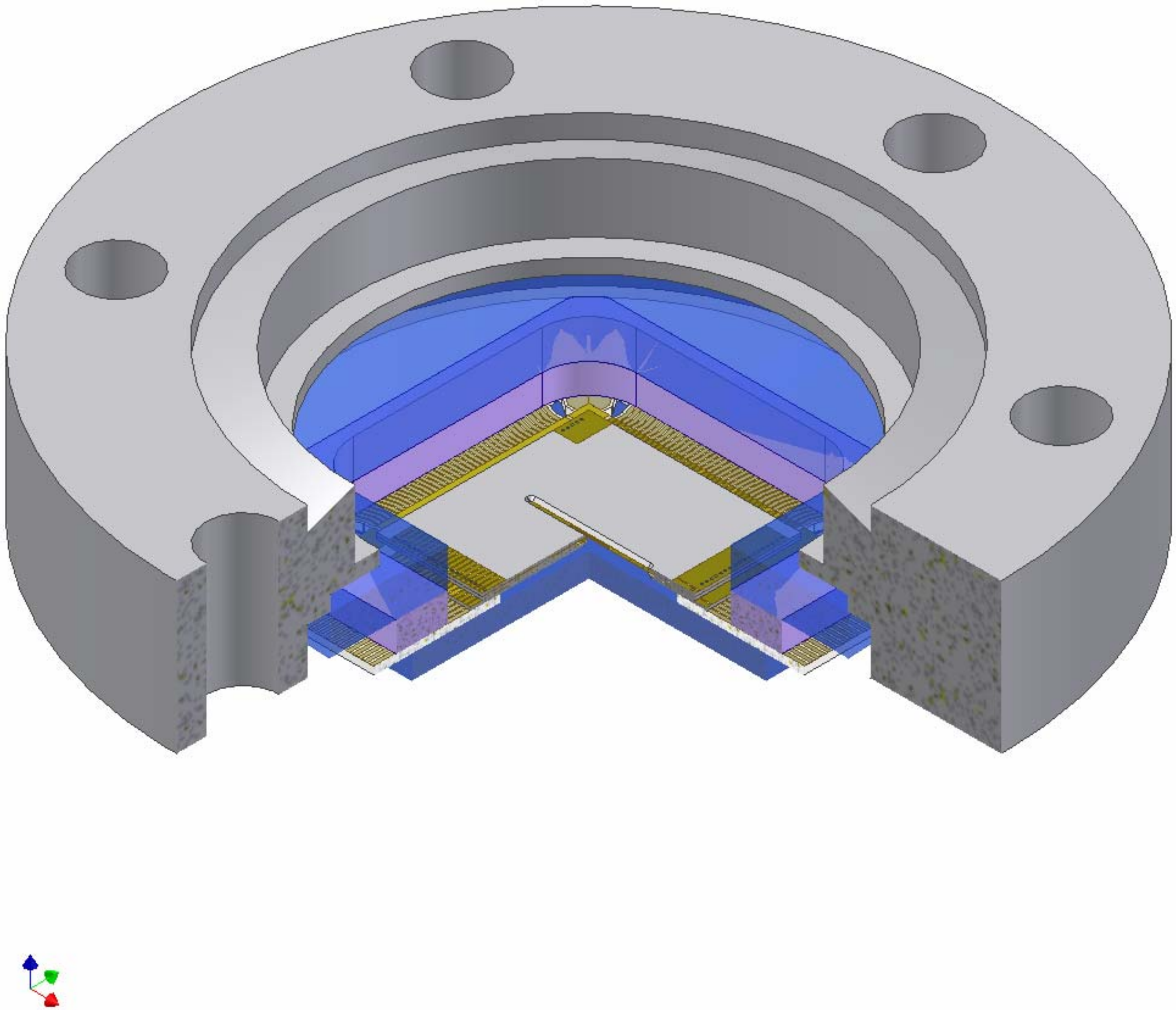
ceramic spacer

conflat flange



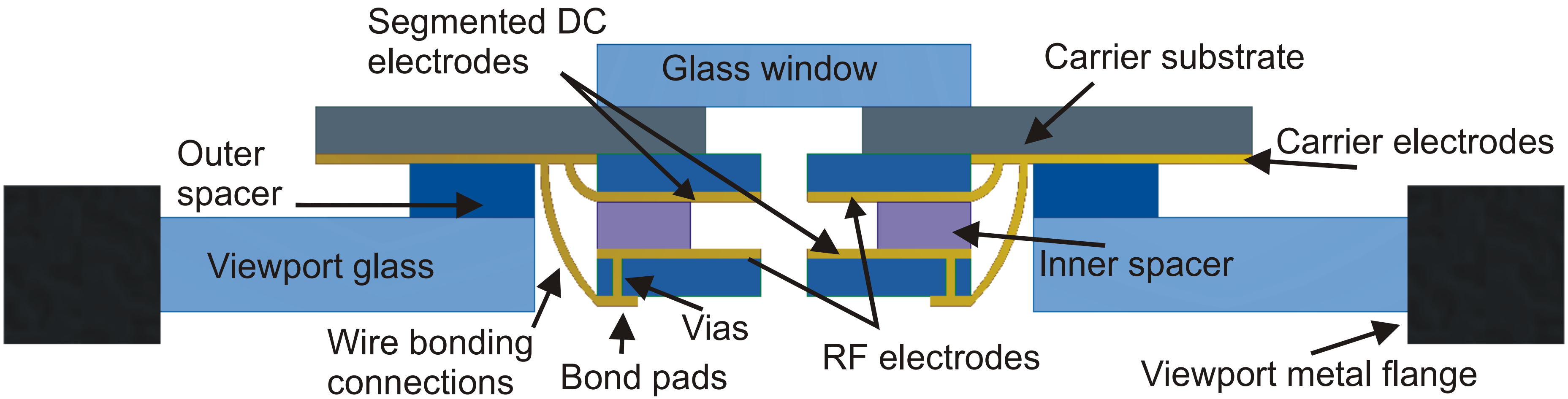
F. Splatt, W. Hänsel

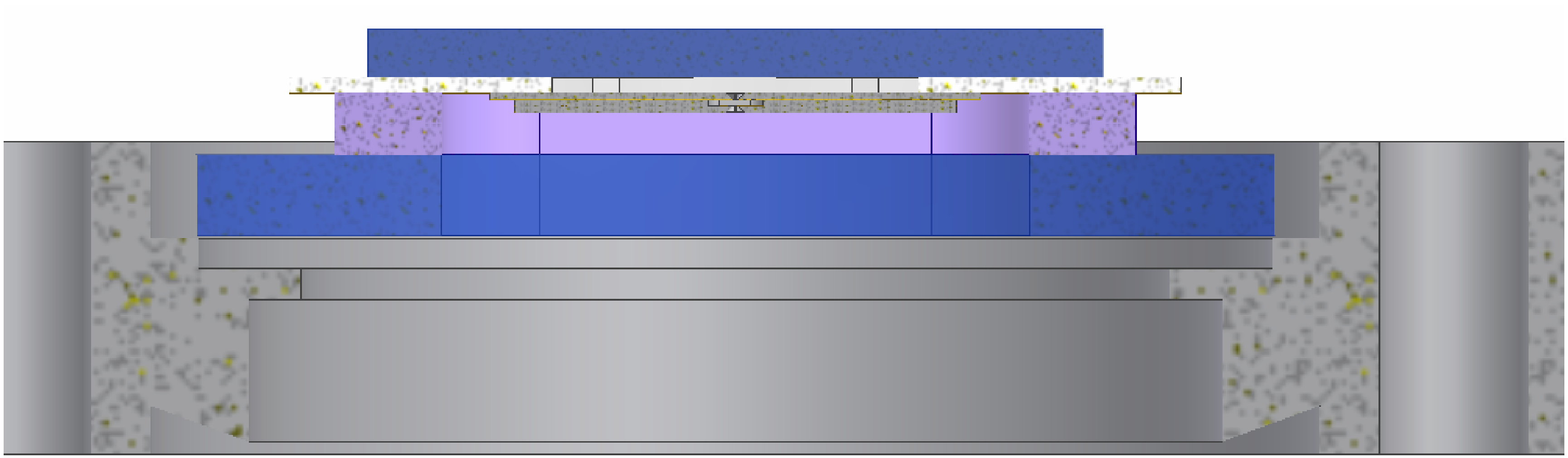
Flange mount



Cross sectional view of trap mounted in flange

(schematic only - not to scale)

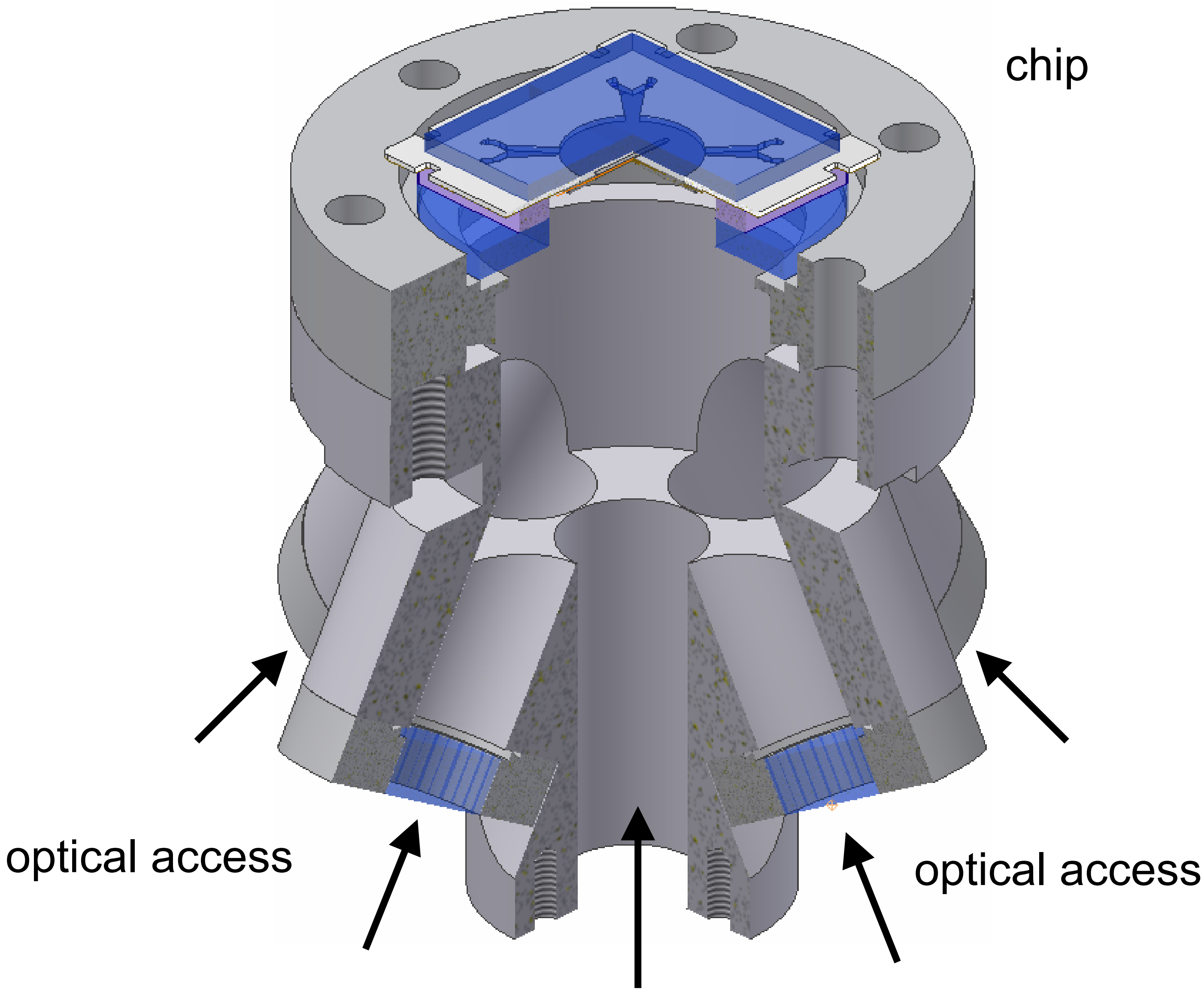




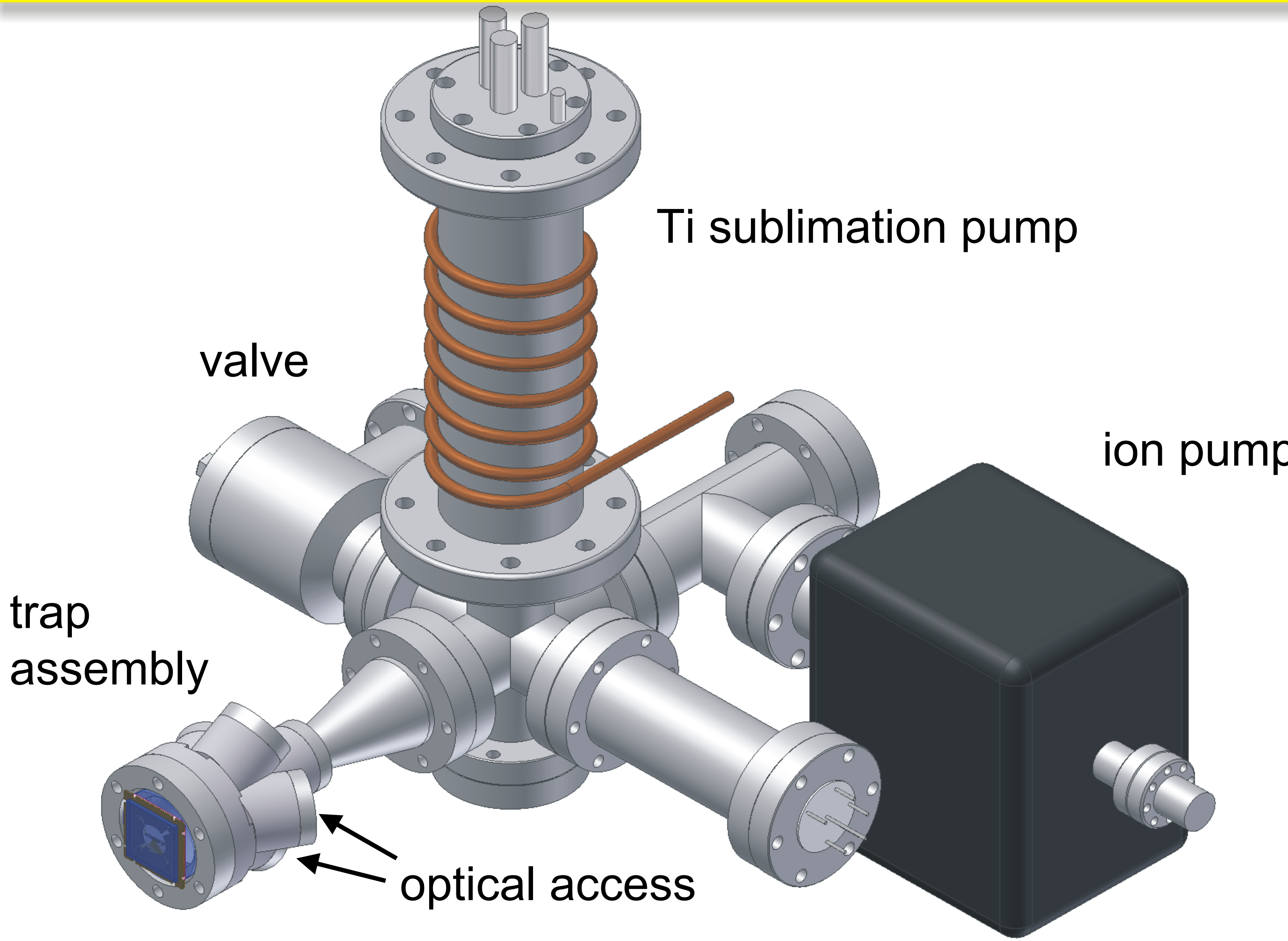
(to scale)

F. Splatt, 2006

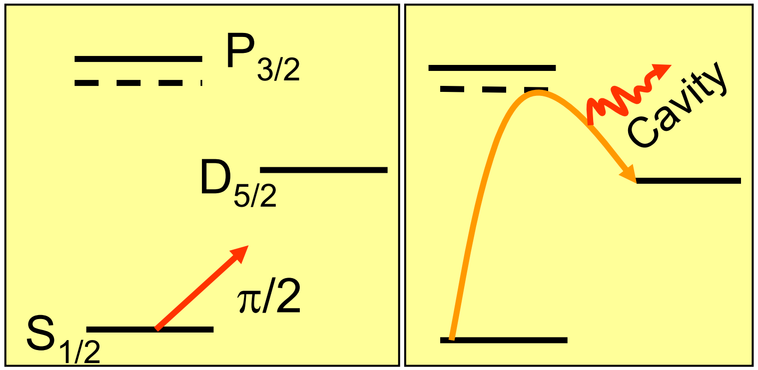
Cross section of mounted flange



Entire vacuum apparatus

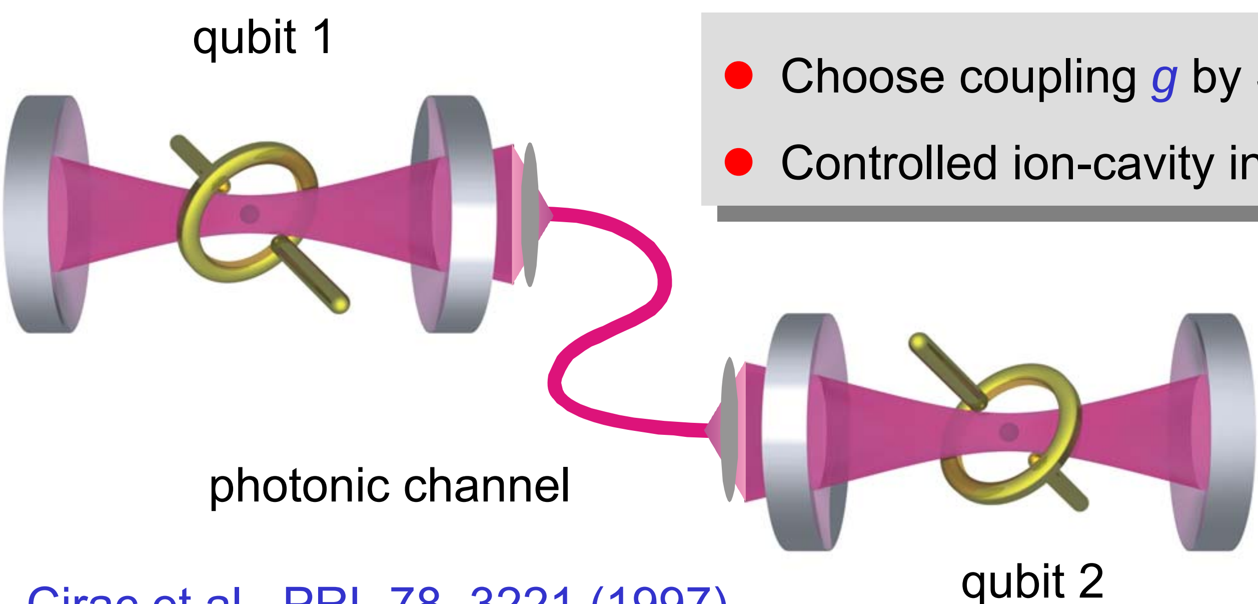


Qubit interfacing: transferring quantum information



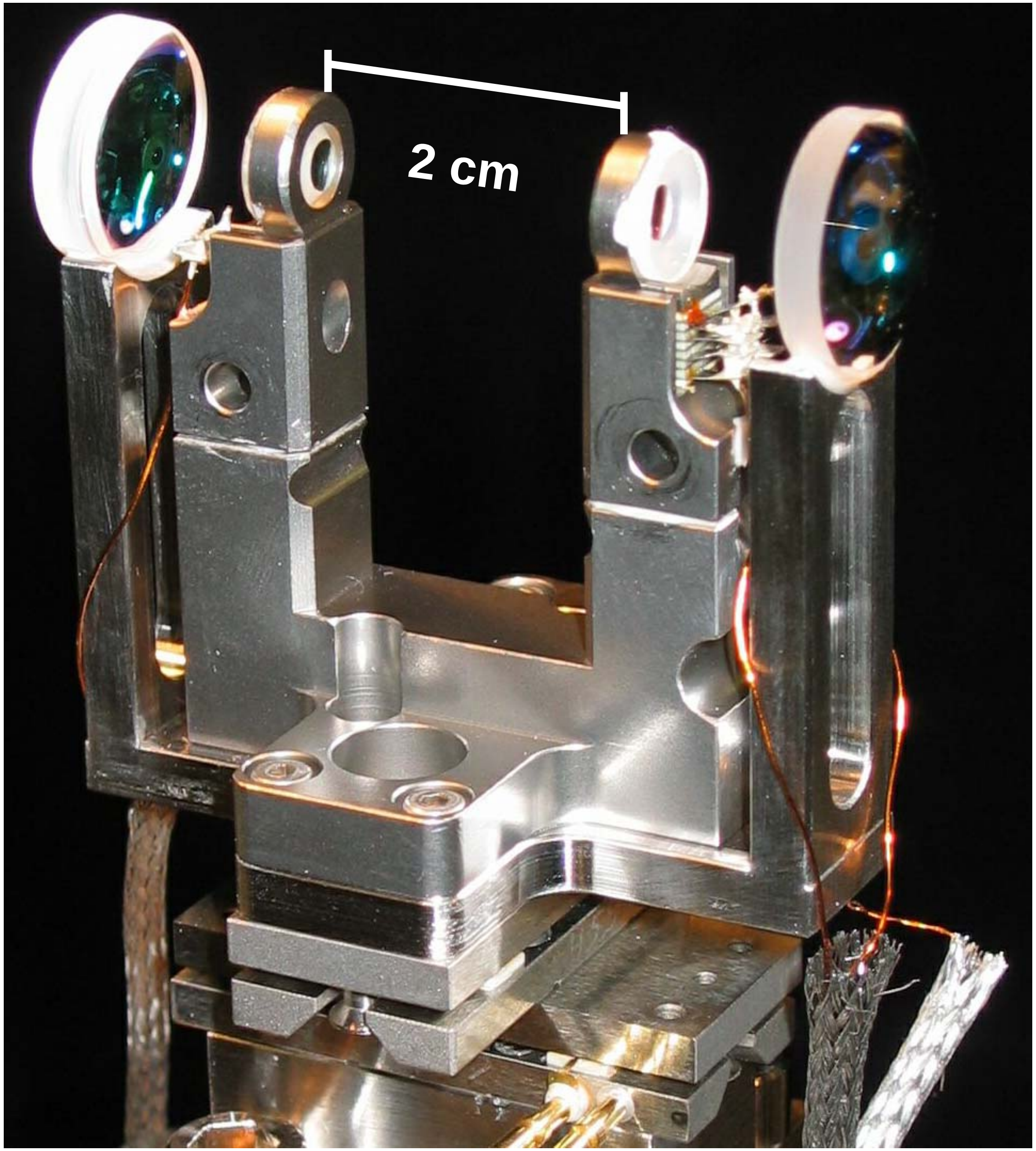
- Transfer quantum state of the ion to cavity photon: qubit interface
- Create superposition photon state (STIRAP)
- Detect cavity output and ion state

- Choose coupling *g* by STIRAP detuning
- Controlled ion-cavity interaction

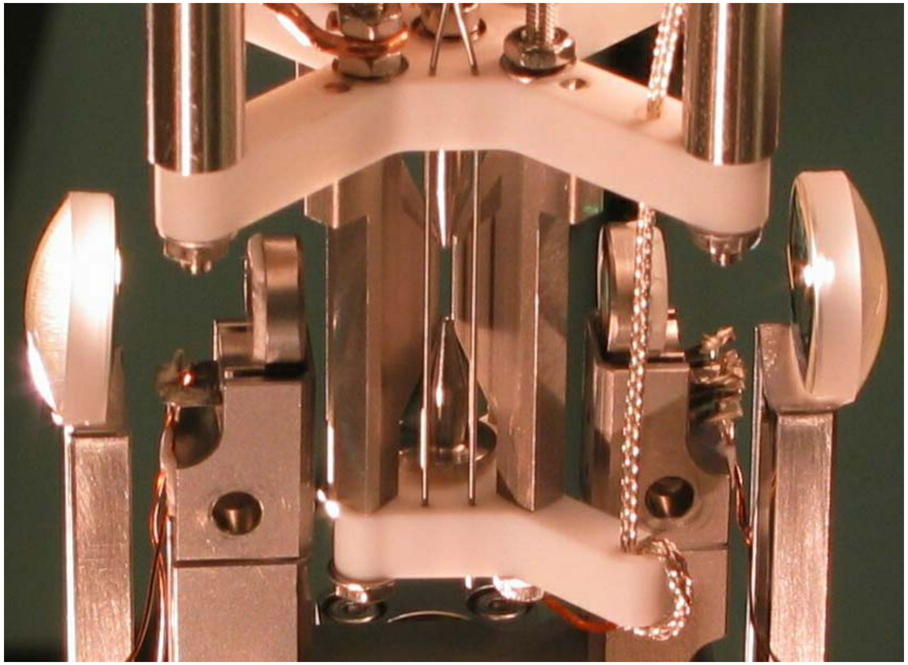


J. I. Cirac et al., PRL 78, 3221 (1997)

Cavity and ion trap (2004)



Cavity and ion trap as single photon source

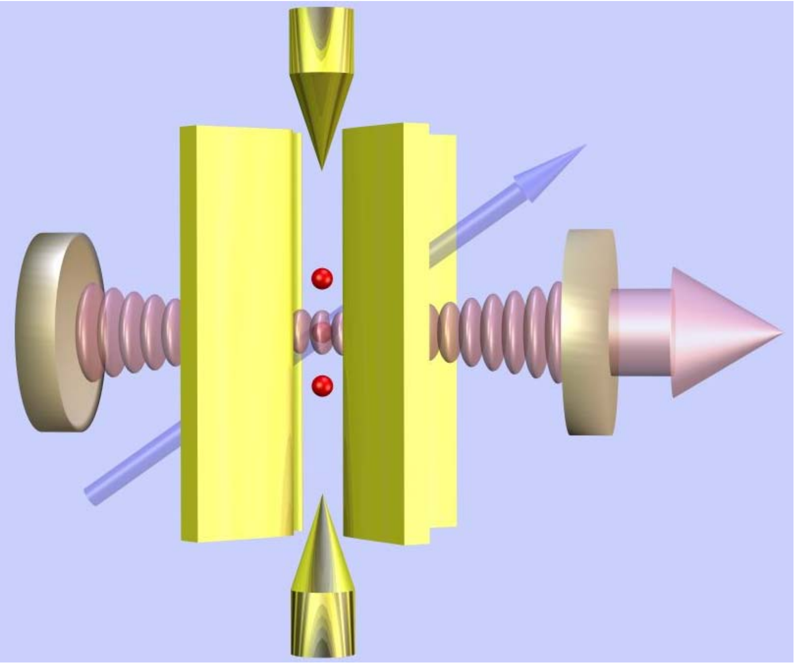


2 cm

Finesse ~ 80000

waist ~ 13 μm
(nearly concentric cavity)

expect ~ 20 kHz single photons
with ~ 90% emission into cavity



details:

C. Maurer, C. Becher et al.
New Journ. Physics **6**, 94 (2004)

Vision: going smaller, merging with ion chip

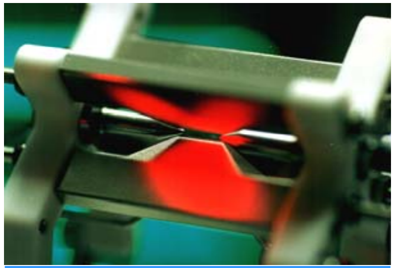
Achieve strong coupling: small mode volumes

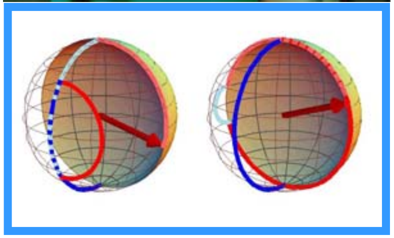
Estimate for $g = \Gamma = \kappa$:	cavity length	L = 1mm
	Finesse	F = 6.800
	waist size	w_0 = 6.5 µm

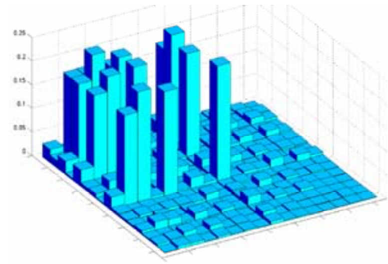
cf. J. Reichel, T. Hänsch et al., 2005

Quantum information processing with Ca^+ in Innsbruck

- state of the art: up to 8 qubits, flexible operations
- long lived entanglement (~ 20 s)
- 4 – 8 particle W-state, full tomography
- error budget, technical improvements
- $^{43}Ca^+$ work in progress
- segmented trap work
- cavity QED towards interfacing ion trap processors



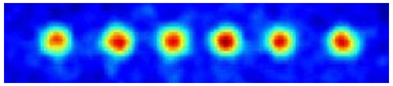


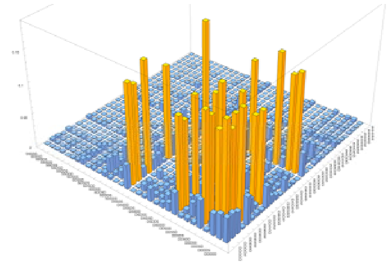


Future:

- optimization of Cirac-Zoller gate (high priority !)

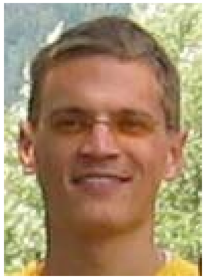
  achieve more CNOT gate operations
- error correction protocols with three and five qubits
- implementation with $^{43}Ca^+$, logical qubits + scalability





Advertising posters of the Innsbruck experiments

- Quantum Process Tomography — M22
  T. Körber
- $^{43}Ca^{+}$ experiment — M14
  J. Benhelm
- Spectroscopy with entangled states — M09
  C. Roos
- Multipartite entanglement — M12
  H. Häffner
- Segmented ion trap project — T13
  W. Hänsel
- Feedback control of a single ion — M06
  J. Eschner



AG Quantenoptik
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The international team 2005

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C. Becher, C. Russo, T. Körber, P. Schmidt, T. Lee

RB, H. Barros, E. Phillips, J. Benhelm, M.Muhkerjee, F. Dubin

P. Moser, P. Pham, H. Häffner, M. Riebe, C. Roos, D. Rotter

M. Chwalla, F. Splatt, U. Rapol, T. Monz, W. Hänsel, D. Chek-al-Kar

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